RECOMMENDATIONS FOR THE DEVELOPMENT LENGTH OF PRESTRESSING STRANDS INCLUDING THE EFFECTS OF HIGH STRENGTH CONCRETE

By

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RECOMMENDATIONS FOR THE DEVELOPMENT

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HIGH STRENGTH CONCRETE

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CHAPTER I

1.0 INTRODUCTION

The use of prestressed concrete in bridge girders is on the rise since its first use more than half the century ago. Owing to the advantages like speed of construction, longer spans, cost efficiency and reliability due to its fabrication in a controlled environment, prestressed bridge girders have rapidly gained popularity. In the last decade, with the introduction of high compressive strength concrete in the prestressing industry, the virtues of using prestressed concrete for bridge girders have been realized even more.

Prestressed concrete mainly relies on the fact that the initial stress in the prestressing strands is transferred to the surrounding concrete, making the entire section in true sense a "pre-stressed" section. Thus, the bond between prestressing steel strands and concrete becomes vital for the structural use of prestressed concrete sections. At any point along the section, loss of this bond between the strand and concrete can lead to sudden failures. Depending on the structural requirements, prestressing strands are being used in variable concrete strengths. Effect of changes in concrete strength on the bond performance is the prime target of this research project. Also, the research aims at relating this effect of changes in concrete strength on strands obtained from different sources.

1.1 BACKGROUND

Transfer and Development lengths of prestressing strands are clear indications of the quality of bond between the strand and concrete. Many researchers in the past have tried to establish a fixed relation between the concrete strength and transfer and development lengths. However, the reviewers of the existing proposed equations suggested that a definite conclusion regarding the concrete strengths could not be obtained because of too much scatter in the data.

An effort to standardize a test to assess the bond quality of the prestressing strands was undertaken at Oklahoma State University and Purdue University. The standardized test called the North American Strand Producer's (NASP) Bond test tries to assess the bonding property of a particular strand in concrete with particular compressive strength. Convincing results obtained from these tests were demonstrated by Brown (2003), Chandran (2006), and Tessema (2006).

Current ACI/AASHTO code provisions do not include the factor for concrete strength while calculating the transfer and development length of prestressing strands. This research aims at evaluating the effects of concrete strength on the transfer and development lengths of prestressing strands.

1.2 RESEARCH OBJECTIVES

The primary aim of this research project is assessing the development lengths of prestressing strands obtained from various sources and having various NASP Pull-Out strengths, in concrete with varying compressive strengths. From the obtained flexural test results an attempt will be made for introducing the factor of concrete strength in the existing (ACI 318-02) /AASHTO equation for development length. Another objective of this research is to compare the results from the NASP Bond test with the experimental values of development lengths for different strands and suggest a minimum NASP Pull-Out strength for adequate anchorage of the prestressing strands.

1.3 TESTING PROGRAM

The experimental program consisted of the flexural tests on two types of beam specimen.

(i) Rectangular Beam Specimen: 43 rectangular beam specimens were fabricated with target release concrete strengths varying from 4000 psi to 10,000 psi. All the beams consisted of two prestressing strands either 0.5 in (12.7 mm) or 0.6 in (15.2 mm) in diameter. These rectangular beams, 17 feet in length, were designed to be tested on each end separately for assessing the development lengths of the corresponding strands. Transfer lengths were calculated on each beam by two methods. First method involved measurements of concrete surface strains at the time of release and then over fixed time intervals. Second method used was by measuring the end slips of the strands before and after release, at fixed time intervals and at the time of testing.

(ii) I-shaped Beam Specimen: In all, 8 I-shaped beam specimens representing the AASHTO Type girder were fabricated with target concrete strengths varying from 6000 psi to 10,000 psi. Four beams specimens with 0.5 in (12.7 mm) diameter strands consisted of 5 strands each while another 4 beam specimens with 0.6 in (15.2 mm) diameter strands consisted of 4 strands each. The central strand at the bottom most level of strands was removed and the position of remaining 4 strands was unchanged. All I-shaped beams were 24 feet long and designed for two separate development length tests on each end. Transfer lengths were determined on each beam using the same procedure as used for the rectangular shaped beams.

CHAPTER II

2.0 BACKGROUND REVIEW

2.1 DEFINITIONS

Several terms are used in the discussion of anchorage behavior of prestressing strands. This section states and explains the definitions of the most significant terms used in the relevant discussions.

2.1.1 Transfer Length

American Concrete Institute (ACI 318-02) defines transfer length, l_t, in its commentary section R12.9 as "the distance over which the strand should be bonded to the concrete to develop the prestress f_{se} in the strand." This arises from the fact that at the free end of the strand the stress transferred to concrete is zero. Stress transferred to the concrete gradually builds up over the length of the prestressing strand and at a certain point assumes a value of f_{se} which remains constant through the length of the beam up to a similar point from the opposite end.

ACI 318-02 specifies the value of transfer length, l_t, as,

$$l_t = \left(\frac{f_{se}}{3}\right) d_b$$

where, d_b = strand diameter in inches and,

f_{se} = effective prestress in the strand after all losses, expressed in kips/in^2.

American Associations of State Highway and Transportation Officials (AASHTO) LRFD Bridge Design Specifications suggests the value of transfer length to be taken as,

$$l_t = 60d_b$$

where, d_b = strand diameter in inches.

Similar to the idealized relation between steel stress and the distance over which the strand is bonded mentioned in ACI 318-02, AASHTO considers the gradual buildup of the strand force with 0.0 at the point where bonding commences to maximum at the transfer length. Section 5.11.4 in AASHTO code specifications discusses the requirements for the development of prestressing strands.

Since the transfer of prestress takes place over a bonded length; precisely "transfer length", it does not exist for non-prestressed reinforcement in concrete. In other words, transfer length indicates required bonded length of reinforcement to completely transfer the "prestress" to the concrete; it has no meaning for the members where there is no "prestress".

2.1.2 Flexural Bond Length

Stress in the strand at the nominal capacity, f_{ps}, is higher than the effective prestress f_{se}. To develop this additional stress, an additional bonded length beyond the transfer length of the strand is required. This required bonded length of the strand in addition to the transfer length for developing the stress equal to f_{ps} at the nominal capacity of the member, is termed as flexural bond length.

2.1.3 Development Length

Development length, l_d, of prestressing strands is defined as the minimum distance from the free end of the strand, over which the strand should be bonded to concrete, so that the section under consideration achieves its full nominal capacity. Hence, it is the entire distance over which the stress in the strand increases from zero (at the free end) to f_{ps} at nominal capacity of the section under consideration. According to ACI 318-02, development length is defined as the sum of transfer length and the flexural bond length. The code (ACI 318-02) gives an expression for development length in section 12.9.1 as follows,

$$l_d = \left(\frac{f_{se}}{3}\right) d_b + (f_{ps} - f_{se})\, d_b$$

where, f_{se} and d_b are as defined above and,

f_{ps} = stress in prestressed reinforcement at nominal strength expressed in kips/in^2.

AASHTO LRFD Bridge Design Specifications, 1998 specifies a similar development length in section 5.11.4.2 and demands a development length given by following expression,

$$l_d \geq \kappa\left(f_{ps} - \frac{2}{3} f_{pe} \right) d_b$$

where,

d_b= nominal strand diameter (in.)

f_{ps}= average stress in prestressing steel at the time for which the nominal resistance of the member is required (ksi)

f_{pe} = effective stress in the prestressing steel after losses (ksi)

κ = 1.6 for precast, prestressed slabs and piles.

= 1.6 for precast, prestresssed beams κ may be specified for these items by the authority having jurisdiction, based on the research or prior successful use.

Figure 2.1 represents the idealized variation of strand stress which might be used for analyzing sections within the development length region as presented by Commentary R12.9.1.1 in ACI 318-02.

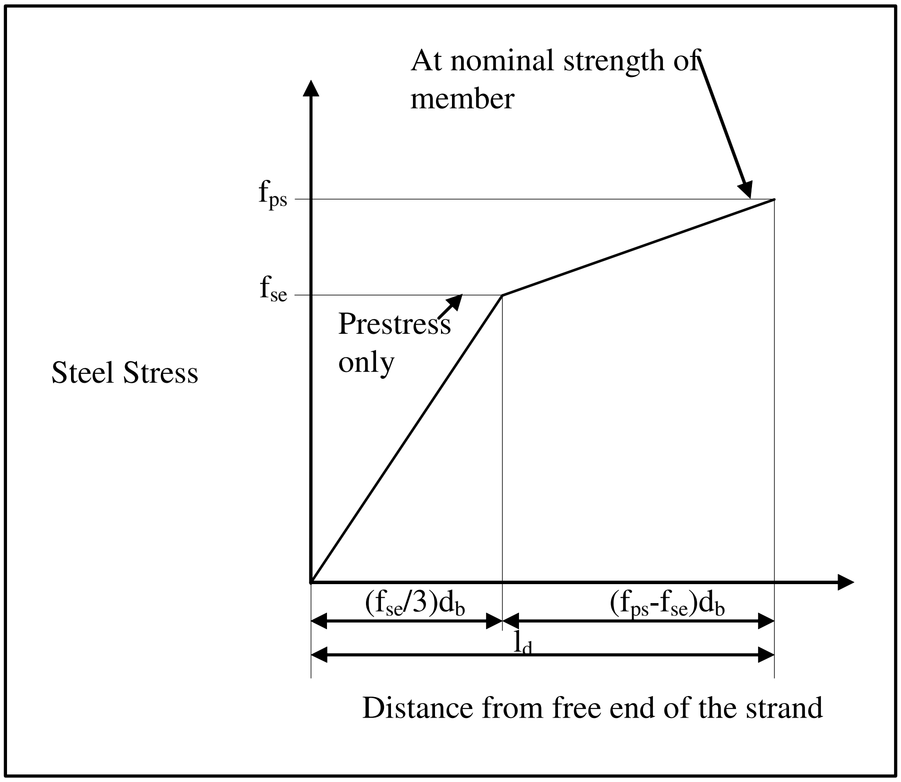

Figure 2.1: Idealized bilinear relationship between steel stress and distance from the free end of strand ACI 318-02 Fig. R12.9

Since development length is the length over which the reinforcement develops the amount of stress equal to its value at the nominal capacity of the member under consideration, it exists in both prestressed and non-prestressed reinforcements. In non-prsetressed reinforcement, stress at nominal capacity is essentially the yield stress, f_y. Therefore, for non-prestressed reinforcement, development length indicates a minimum distance over which the reinforcement should be bonded so that the value of stress increases from zero (at the end) to f_y at the nominal capacity of the member considered.

2.2 PREVIOUS RESEARCH

This section contains brief summaries of the research conducted earlier regarding the bond between prestressing strands and concrete.

2.2.1 Homayoun H. Abrishami and Denis Mitchell (1993)

A new approach to study the bond characteristics of pretensioned strand was proposed by this (Abrishami 1993) research project. The technique involved determination of average bond stresses in the transfer length and flexural bond length by performing tests on models which simulate the bond actions in transfer and flexural bond length regions. For simulating bond behavior along the transfer length, prestress was released in a controlled fashion over a prestressed concrete segment and end slip readings were noted at both ends. Also, for simulating the flexural bond behavior, stress at one end of the segment was increased in a controlled fashion and end slips were noted at both ends. The results of these tests led to the conclusion that occurrence of end slip at the free end starts after the peak bond stress is attained. This concept was used to identify bond failures during the flexural tests conducted on the beam specimen.

2.2.2 Robert W. Barnes and Ned H. Burns

An investigative research was conducted for studying the anchorage behavior of 0.6 in diameter strands in High Strength Concrete. This program was one of the early experimental programs attempting to associate the concrete strength factor in the equation for transfer and development length of prestressing strands. As many as 36 AASHTO Type-I I-beams were cast and initial and long term transfer length data was recorded. Also, these I-beams were tested in flexure to assess the development length of the prestressing strand used. The prestressing strands used in these I-beams were obtained from a variety of strand manufacturers and it was observed that the transfer and development lengths of strands obtained from different sources varied considerably. The research concluded that before developing a suitable expression reflecting the bond behavior based on their experimental results, a bond performance standard should be adopted or the source of disparity in bond behavior should be identified and addressed. A general trend was established hinting towards an inverse relationship between $\sqrt{fci'}$ and transfer lengths but with too much scatter. Also the researchers could not relate concrete strength to development length. The current experimental program aims to reduce the uncertainty in relating concrete strength to transfer and development lengths of prestressing strands.

2.2.3 Bruce Wayne Russell (1992)

The main objectives of the research conducted at University of Texas at Austin (Russell 1992) were (i) to determine the transfer and development length of both 0.5 in and 0.6 in. diameter prestressing strands and (ii) to develop design guidelines for the use of debonded strands in pretensioned concrete. Developing a rational understanding of the bond mechanisms between concrete and prestressing strand was the generalized objective of the research project. For assessing the development lengths of 0.5 in. and 0.6 in.

diameter strands, a series of development length tests were performed on scale model AASHTO-type specimen of both rectangular and I-shaped cross-sections. By systematically changing the embedment length, development length defined as "the embedment length that borders between flexural failure and bond failure" was estimated to be 72 in. for 0.5 in. strands and 84 in. for 0.6 in. strands.

One of the important observations made regarding I-shaped cross-sectioned beams was "the web shear cracking was found to precipitate bond failure". This phenomenon was supported by the following discussion. With a crack of finite width, either flexural or shear extends across a prestressing strands, a finite slip of strand is inevitable. This results in development of additional tensile stress along the strand adjacent to the crack. Since web shear cracks tend to propagate near the anchorage zones, they are more likely to cause strand slips than the flexural cracks which tend to occur near the center span. These strand slips caused propagation of cracks across the strand in the anchorage zone were caused due to the loss of Hoyer's effect and increased tensile requirement of strands owing to the shear loads from the concrete adjacent to the cracks being transferred to the strands. Hoyer's effect is one of the elements of bond along with the adhesion and mechanical interlocking. Hence the loss of one of the elements of bond reduces the bonding capacity of the prestressing strands.

As web shear cracking occurs usually in I-shaped beams due to thinner webs and is not as probable to occur in rectangular beams, the rectangular beams exhibited shorter development length requirements. This observation was also made during the flexural tests carried out as a part of the ongoing research project and it forms the reason for selecting the data from development length tests on rectangular beams alone for evaluating the development length equation.

Rectangular beams (Russell 1992), which were made with 0.5 in strand suffered from “poor bond”. This was evident from the longer transfer and development lengths in comparison with the results from other beam series. As the rectangular beams with 0.5 in. strands failed in bond even at embedment lengths higher than the code provisions existing at that time, the code provisions were concluded to be inaccurate to portray the beam behavior. On the other hand, for 0.6 in. strands, the development length test results proved that the code provisions were conservative.

2.2.4 Deatherage, Burdette and Chew (1994)

A research was conducted at the University of Tennessee (Deatherage 1994), wherein, 20 AASHTO Type-I beams were tested in flexure in response to an FHWA memorandum of 1988 which restricted the use of certain sizes of seven wire prestressing strands. Twenty full-scale AASHTO Type-I beams with various strand diameters were being tested in flexure. As opposed to the restriction imposed on the use of 0.6 in diameter strands in the memorandum of 1988, the test results showed that these strands in fact had shorter transfer lengths in relation to their diameter as compared with other sizes of strands. Development lengths as evaluated by the tests were comparable to other strand sizes. Owing to higher steel area, use of 0.6 in. diameter strands led to increased moment capacities. Another restriction in the FHWA memorandum was on the minimum spacing of strands, it was restricted to 4 times the strand diameter. However, tests conducted on beams with 0.5 in. diameter strands with 1.75 in. spacing demonstrated moment capacities which were not significantly different from those obtained with 2.0 in. strand spacing. One of the conclusions that the researchers made is of special importance to our research project and it was as follows "Increasing the development length for all strand sizes to 1.6 times the value obtained from the AASHTO equation is not justified."- (Deatherage 1994)

2.2.5 John Jacob (1998)

John Jacob (1998) carried out eight development length tests on four I-shaped beams with the cross-section similar to the I-shaped beams being tested as a part of the ongoing research project. The purpose of this experimental program was to demonstrate the effectiveness of horizontal shear reinforcement in preventing strand anchorage failures and help develop basic design guidelines for the inclusion of horizontal web shear reinforcement in the end regions of prestressed concrete girders. Importance of Jacob's experiments to our research project is that they established the basic test procedure which was followed for development length tests on I-shaped beams at Oklahoma State University as a part of the current research.

I-shaped beams tested by Jacob were approximately 3/8th scale AASHTO Type IV prestressed concrete bridge girders same as the cross-section of the I-shaped beams tested as a part of the ongoing research. During the development length tests carried out by Jacob, it was found that the initial beams suffered concrete crushing in the bottom bulb. As a result, external hoop reinforcement had to be provided during further tests. The internal hoop reinforcements provided in I-shaped beams under consideration were provided so as to avoid similar concrete crushing in the bottom bulb.

It was observed from the results of flexural tests that shear cracks formed in the transfer region lead to premature failures of the sections. Also, the additional shear reinforcement provided in the beams preserved the strand anchorage leading to increased ductility and occasional flexural failures. The research was concluded with recommendations for including enough horizontal web reinforcement for achieving fairly good estimates of beam capacities.

2.2.6 Peterman, Ramirez and Olek (2000)

Eighteen development length tests on single strand rectangular and multiple strand T-shaped beams made of semi-lightweight concrete having compressive strength of 7000 psi (48MPa) (Peterman 2000) were carried out as a part of this research project. Two different strands "A" and "B" were used in these beam specimens and the results from the T-shaped beam flexural tests showed that all beams with strand "A" had a flexural failure while for beams with strand "B" had bond failures in three of four specimens. It was also noted that for specimens with strand "B", flexural shear cracks were formed before the bond failures. Researchers claimed a shift of critical section from the point of maximum moment towards the free end of the strand. Considering this shift of critical section, it was recommended that requirements of strand development length be enforced at a distance of d_p from the point of maximum moment where d_p is the distance between the extreme compression fiber and the centroid of prestressing reinforcement. Alternatively, it was recommended that "..the designer may elect to provide enough transverse reinforcement to minimize the shift in tensile demand that will occur in the event of diagonal cracking."

2.2.7 Shing, Cooke, Leonard, Frangopol, McMullen and Hutter (2000)

Flexural tests on prestressed box girders made of high performance concrete to investigate transfer and development length requirements of Grade 270, 0.6 in. prestressing strand (Peterman 2000) were carried out. Concrete used in these specimens had a specified compressive strength of 10,000 psi. Detachable mechanical (DEMEC) readings were taken to measure the concrete surface strains from which the transfer lengths were determined. In all, six flexural tests were conducted and the provided embedment lengths were determined from the results of the preceding tests. Based on the mode of failure (bond failure or flexural failure), the development length was estimated to be the maximum embedment length at which bond failure occurred. Embedment length (l_e) used for the first test was 85 in. and it was taken as the average of the development lengths obtained from previous research. Since the first test resulted in flexural failure, l_e was reduced for the next test and this trend continued as long as the result of flexural test was flexural failures. Following embedment lengths were used after the first test – 81in, 76 in, 65 in, 60 in, and 59 in. The results for $\boldsymbol{l_e}$ of 76 in. and 65 in. were flexural failures along with very small values of end slips. The researchers suggested that the development of shear cracks in the transfer zones which led to the localized increase in strand stress may have been the cause of end slips. First instance of bond failure occurred at $\boldsymbol{l_e}$ = 60 in. which led the researchers to conclude that the required development length was between 60 in. and 65 in. Comparison of development length of 60 in. with the value obtained from AASHTO/ACI equations showed that these AASHTO/ACI equations overestimate development length by 53 percent. Also, average value of transfer length as determined from the measurement of surface strains was 18 percent higher than the value calculated using AASHTO/ACI equations. The study finally concluded that the AASHTO/ACI transfer and development length requirements were adequate for the girders used in this research. However, the study was limited to six flexural tests, which was thought to be insufficient to make general design recommendations by the researchers.

2.2.8 Kahn, Dill and Reutlinger (2002)

For the purpose of verifying the validity of equations for calculating transfer and development lengths of 0.6 in. diameter prestressing strands specified in AASHTO Specifications (1996), an experimental research program was carried out which included testing of four AASHTO Type-II girders. Two of these girders were made from 10,150 psi concrete, while the other two were made from 14500 psi concrete. Transfer lengths were determined from the measurements of end slip and concrete surface strains at the level of prestressing strands (Russell 1992). For determining the development length, eight flexural tests were performed on the beam specimens with varying embedment lengths. Methods to measure transfer lengths and development lengths at Oklahoma State University were the same. Previously (Kahn 2000) had proved that the effective span lengths of AASHTO bridge girders could be increased by 40% reducing the number of girders required, by using 0.6 in. diameter strands with High Performance Concrete up to 14,500 psi as compared to using the same strands in normal (40 MPa) 5800 psi. The experimental verification was required for assurance of the effectiveness of the above mentioned claim. From the results obtained from the flexural tests and measurements of transfer lengths, the researchers concluded that "..0.6 in. diameter prestressing strands showed good bond and development characteristics in high performance concrete with compressive strengths less than 14500 psi and therefore, are recommended for use in pretensioned HPC bridge girders." Also, the transfer lengths were found to be 41% and 51% lesser and the development lengths were 20% lesser than the calculated values from specified equations in AASHTO (1996).

2.2.9 Matthew D Brown and Dr. Bruce W Russell (2003)

To assess the validity of standard pull-out tests including the Moustafa Pull-Out Test Method, PTI Bond Test Method and NASP Pull-Out Test method, identical pull-out and flexural tests were performed (Brown 2003) on strands obtained from various manufacturers. The main area of interest to our research project would involve the comparison between NASP Pull-Out test results and the flexural test results.

Flexural test program included 16 rectangular shaped beams of the size 6.5 in X 12 in. cross-section and 18 feet length. Eight of the beams were configured to carry single prestressing strand while the other 8 were configured to carry two strands. The double strand beams were similar in cross-section to the rectangular shaped beams that were tested as a part of the current research project. Flexural tests were also carried out in a similar fashion as for the rectangular beams as a part of this project. Table 2.1 and Table 2.2 summarize the flexural test results as obtained by Matthew D. Brown. These tables also include the Average NASP Pull-Out values of the prestressing strands used in each of the beams.

Table 2.1: Single Strand Beam Failure Mode Summary (Matthew Brown 2003)

Beam Tests on Rectangular Beams by Matthew Brown (2003) - Single Strand Beams				
Beam No.	**fc' 56 days**	**Average NASP P.O Value**	**Embedment Lengths (in.)**	
	(psi)	**(lbs.)**	**58**	**73**
II11	6290	4140	B	F
II12	6280	4140	B	B
FF11	6260	7300	V	F
FF12	6070	7300	B	F
HH11	6330	10700	F	F
HH12	6300	10700	B	F
AA11	6220	14950	F	F
AA12	6160	14950	F	F
F = Flexural Failure				
V = Shear Failure				
B = Bond Failure				

Table 2.2: Double Strand Beam Failure Mode Summary (Matthew Brown 2003)

Beam Tests on Rectangular Beams by Matthew Brown (2003) - Double Strand Beams				
Beam No.	**fc' 56 days**	**Average NASP P.O Value**	**Embedment Lengths (in.)**	
	(psi)	**(lbs.)**	**58**	**73**
II21	6290	4140	B	F
II22	6280	4140	B	B
FF21	6260	7300	F	F
FF22	6070	7300	F	F
HH21	6330	10700	F	F
HH22	6300	10700	F	F
AA21	6220	14950	F	F
AA22	6160	14950	F	F
F = Flexural Failure				
V = Shear Failure				
B = Bond Failure				

Statistical correlation performed by Brown, comparing the test results from the Pull-Out tests and the flexural tests, showed that the NASP Bond Test method had strongest correlation as compared to the Moustafa Pull-Out Test method and the PTI Bond Test method. A further investigation of NASP test was recommended as it could not be used conclusively to accurately predict bond performance.

Results from Brown's flexural tests and the corresponding NASP Pull-Out values will be used in the discussions of the current research project as an attempt to suggest a threshold NASP value for prestressing strands to achieve adequate anchorage of bond within the specified development length.

2.2.10 Kiran Chandran (May 2006)

A research program sponsored by National Cooperative Highway Research Program (NCHRP) was carried out at Oklahoma State University (Chandran 2006) for assessing the quality of prestressing strands with NASP Pull-Out tests. The primary objective of the research program was to standardize a single pull-out test method that would give repeatable and reproducible results. Rectangular and I-shaped beams cast as a part of the ongoing research project were used for the measurement of transfer lengths at release and over extended time intervals. Figure 2.2 shows the nomenclature used by Chandran which is consistent with the nomenclature used in the ongoing research. Comparison between the measured transfer lengths and the NASP Pull-Out strengths of the corresponding strands were included for discussions as a part of the Masters Thesis by Kiran Chandran. NASP Pull-Out values for all the strands as used in the ongoing research and also the transfer length data for all the beams being tested in flexure in the current research are adopted from Kiran Chandran's Masters Thesis.

Following were the conclusions made (Chandran 2006) which are of special importance to the ongoing research project.

“1.The NASP Bond test can be performed on 0.5 in. and 0.6 in. diameter Grade 270 low relaxation strands.

2. The transfer length is a function of the concrete strength. Higher the concrete strength, lower the transfer lengths.

3. The pull out force from the NASP bond test is inversely proportional to the transfer lengths.”

Chandran (2006) also recommended that the ACI 318-02 code equation for calculating the transfer length should have a factor that will include the concrete strength.

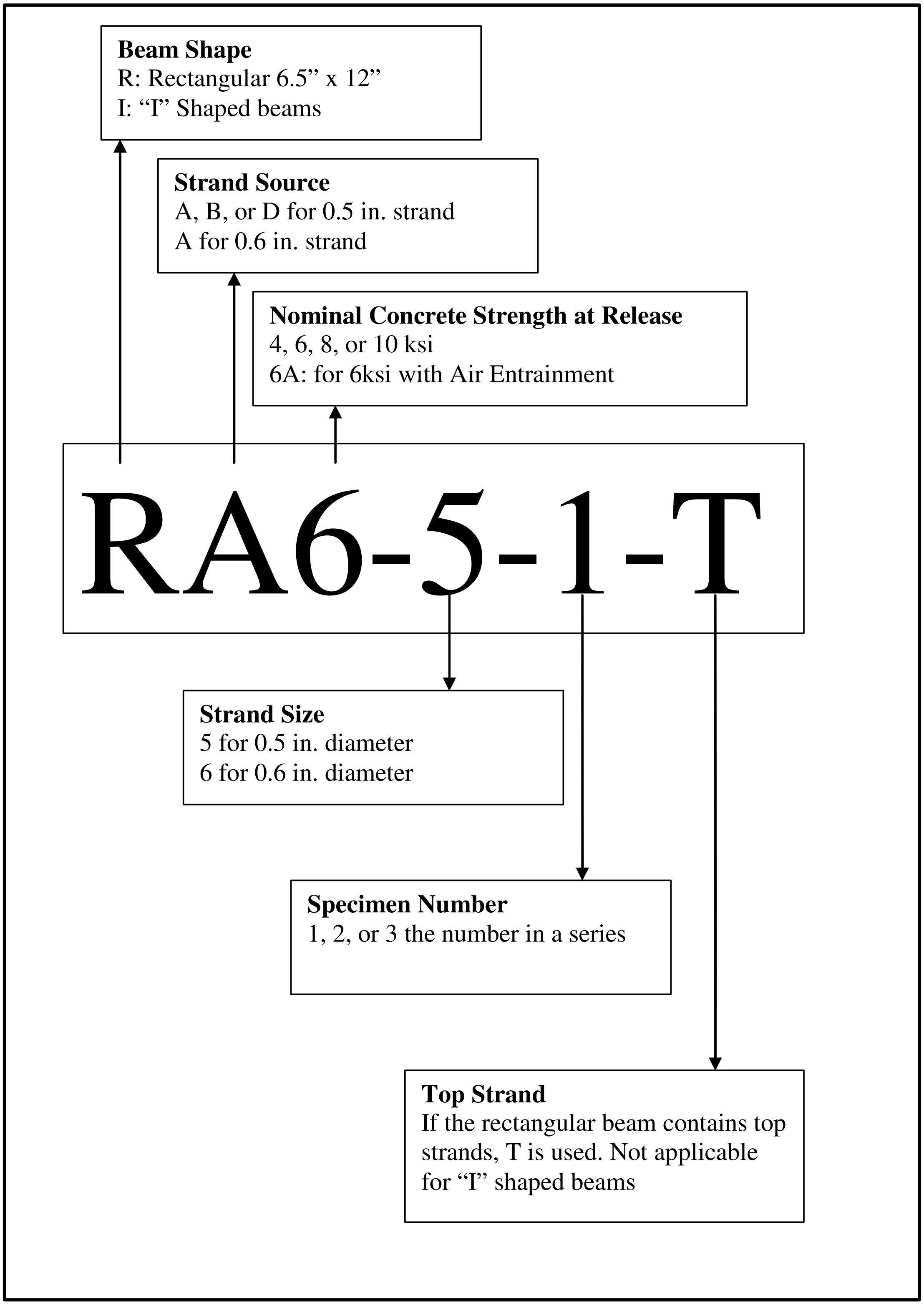

Figure 2.2: Nomenclature for beam specimens used adopted for the current research project. Adopted from Masters thesis of (Chandran 2006)

CHAPTER III

3.0 DEVELOPMENT LENGTH TESTS

Development length tests were carried out on a single end of the beam at a time. A predetermined embedment length determined the loading geometry. Load was applied on the beam at two points using a spreader beam in such a way as to obtain a constant moment region between the two load points. Loading was continued till the beam failed either in flexure, shear, bond or the beam continued to deflect significantly without any considerable increase in the load value. The material properties, section properties, load frame used, loading geometry and the detailed procedure followed for every test is described in this chapter.

3.1 MATERIAL PROPERTIES

Rectangular and I-shaped beams were fabricated using seven wire 270 ksi low relaxation strands obtained from different sources and each conforming to ASTM A416 specifications. Detailed properties of these strands are mentioned in Table 3.1.

Table 3.1 : Properties of the Prestressing strands

	0.5 in diameter	0.6 in diameter
Nominal Diameter (in.)	0.5	0.6
Nominal Diameter (mm)	12.7	15.2
Nominal Crossectional Area (sq. in.)	0.153	0.217
Nominal Crossectional Area (mm^2)	98.7	140
Modulus of Elasticity (ksi)	28500	
Modulus of Elasticity (Gpa)	196.3	

Cement used in the concrete for all the beams, was Type III cement from Lafarge North America. Coarse and fine aggregates were obtained from Dolese Brothers while Cement slag and admixtures were obtained from Lafarge North America and Degussa Admixtures Inc. respectively. Concrete mix design was performed by Eden Tessema (2006) and the details of mix design are out of the scope of this thesis. Table 3.2 mentions the mix proportions and the target fresh and hardened properties of concrete used for all beams. The nomenclature for these mix designs are adopted from (Tessema 2006) and (Chandran.2006) For Table 3.2, C-0, C-I, C-II and C-III specifies the concrete with concrete release strength of 4 ksi, 6 ksi, 8 ksi and 10 ksi respectively. C-IA specifies the concrete with air-entrainment.

Table 3.2 : Concrete Mix Proportions (Kiran Chandran 2006)

Material	C-0	C-I	C-IA	C-II	C-III
Cement (PCY)	650	800	800	800	900
Cement Slag (PCY)					100
Coarse Aggregates (PCY)	1800	1703	1800	1805	1747
Fine Aggregates (PCY)	1243	1203	922	1219	1183
Water (PCY)	298	303	272	277	251
Glenium 3200 (fl oz/cm. wt)			10	14	7
Glenium 3400 (fl oz/cm. wt)	8	5			5.5
Polyheed 997 (fl oz/cm. wt)			3		
MB-AE 90 (fl oz/cm. wt)			1.88		
Target Properties for Fresh and Hardened Concrete					
1 Day Strength (ksi)	4	6	6	8	10
28 Day Strength (ksi)	6	8	8	10	16
56 Day Strength (ksi)	8	10	10	14	18
Slump (in)	8	8	8	8	9
Unit Weight (pcf)	145	148	148	150	157
Air Content (%)	2	2	8	2	2

3.2 SECTION PROPERTIES

3.2.1 Rectangular Beams

The cross-section of the rectangular beams was 6.5 in. (width) and 12 in. (height). Length of all the rectangular beams was 17 feet with two strands either both 0.5 in., or both 0.6 in. diameter at 2 in. from the bottom surface. Two #6 bars 16 feet and 8 in. were tied to stirrups places at 2 in. from the top surface of the beams. Stirrups were made of #3 bars bent in a rectangular shape such that they were 2 in. inside from all the sides and with 6 in. spacing. Figure 3.1 shows the cross-section and the reinforcement details for the rectangular beams.

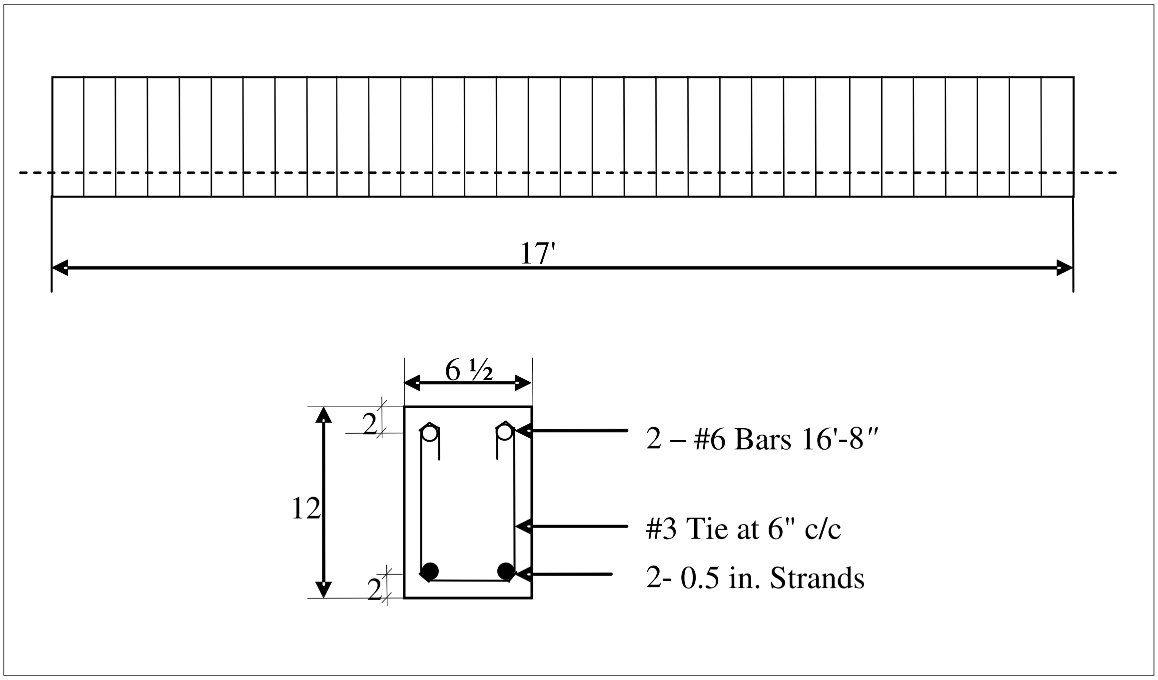

Figure 3.1: Cross-section and reinforcement details of rectangular beams (Chandran 2006)

3.2.2 I-Shaped Beams

Figure 3.2 shows the cross-section of the I-beams with the reinforcement details. Each beam had a length of 24 feet with 5 strands for the beams with 0.5 in. diameter strands and 4 strands for the beams with 0.6 in diameter strands. The central strand from the bottom most level of strands was removed keeping the remaining 4 strands in their respective positions. Top flange longitudinal reinforcement was 2 #3 bars throughout the length and the transverse reinforcement was # 3 bars at 9 in spacing throughout the length of the beams. Stirrups were # 3 bars with standard 90 degree bend and spaced 7 in. on-center. These stirrups were arranged such that the alternate stirrups faced in the opposite directions as shown in Figure 3.3. In addition to these reinforcements, horizontal reinforcement of #4 bars with a standard 180 degree bend on one end were placed near the beam ends with 2 #4 bars on the South end and 4 #4 bars on the North end. To avoid concrete crushing in the bottom bulb, a reinforcement cage as shown in the Figure 3.4 was provided in all I-shaped beams. The vertical reinforcement of this cage was made of #3 bars bent into a triangular shape as shown in Figure 3.5 and the horizontal reinforcement of this cage was made of #3 bars stretched up to 72 in. from the ends of each beam.

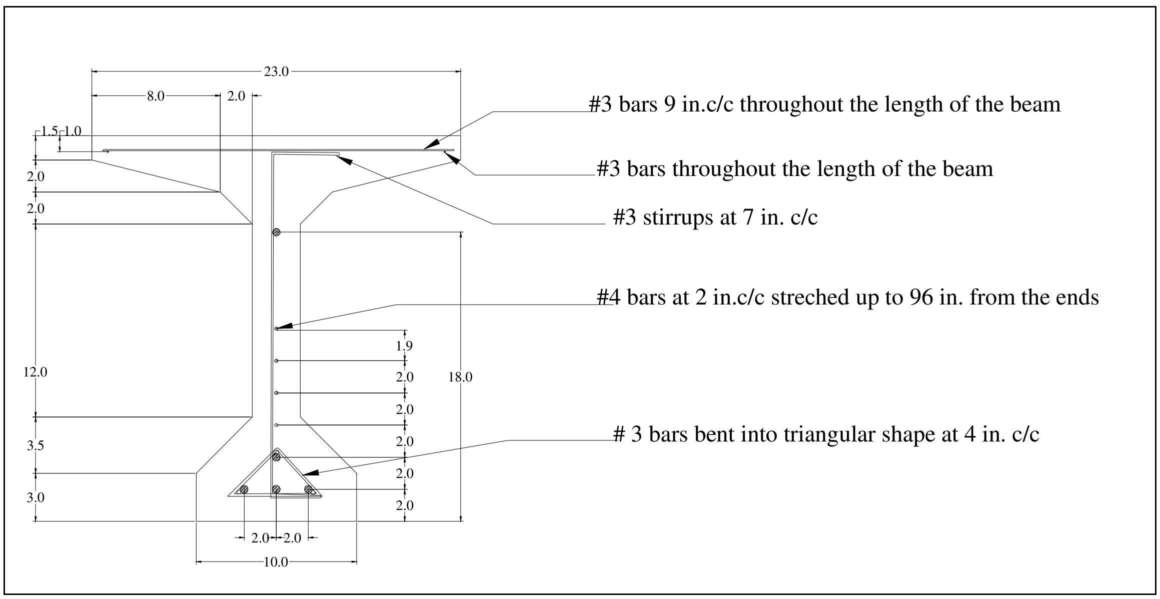

Figure 3.2: Cross-section and Reinforcement details of I-shaped beams

Figure 3.3: Arrangement of stirrups for I-shaped beams

Figure 3.4: Bottom bulb confining reinforcement

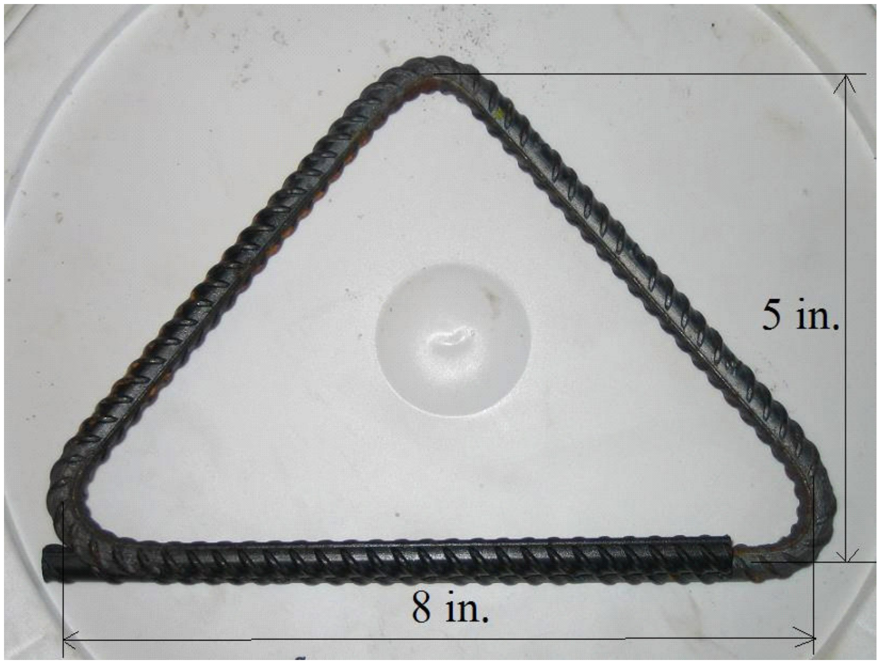

Figure 3.5: #3 bar bent in a triangular shape for bottom bulb confining reinforcement

3.3 TEST FRAME

The test frame was designed to perform flexural tests on the rectangular as well as on the I-shaped beams. Figure 3.6 shows a photo of the test frame with a rectangular beam in position. Test frame mainly consisted of two columns connected to the reaction floor and a crosshead which could be bolted at variable heights depending on different height requirements for rectangular and I-shaped beams. A hydraulic actuator was attached at the center of crosshead so that the line of loading was located at the midpoint between the two columns. A spherical head was attached to the hydraulic actuator which allowed for changes in the slope of the beam during loading. The load was distributed into two point loads by a spreader beam which rested on two small rollers. The position of these two rollers was adjusted to assure a constant moment region between load points on the test beam. The test beam was supported by a pin at the test end and a roller at the opposite end. Figure 3.7 shows the details of the load point between the spreader beam and the test beam. Figure 3.8 shows the support at the "test end" of the test beam. Not pictured in Figure 3.8 are wedges placed underneath the roller on the "test end" of the beam that effectively pins the end thus preventing lateral translation.

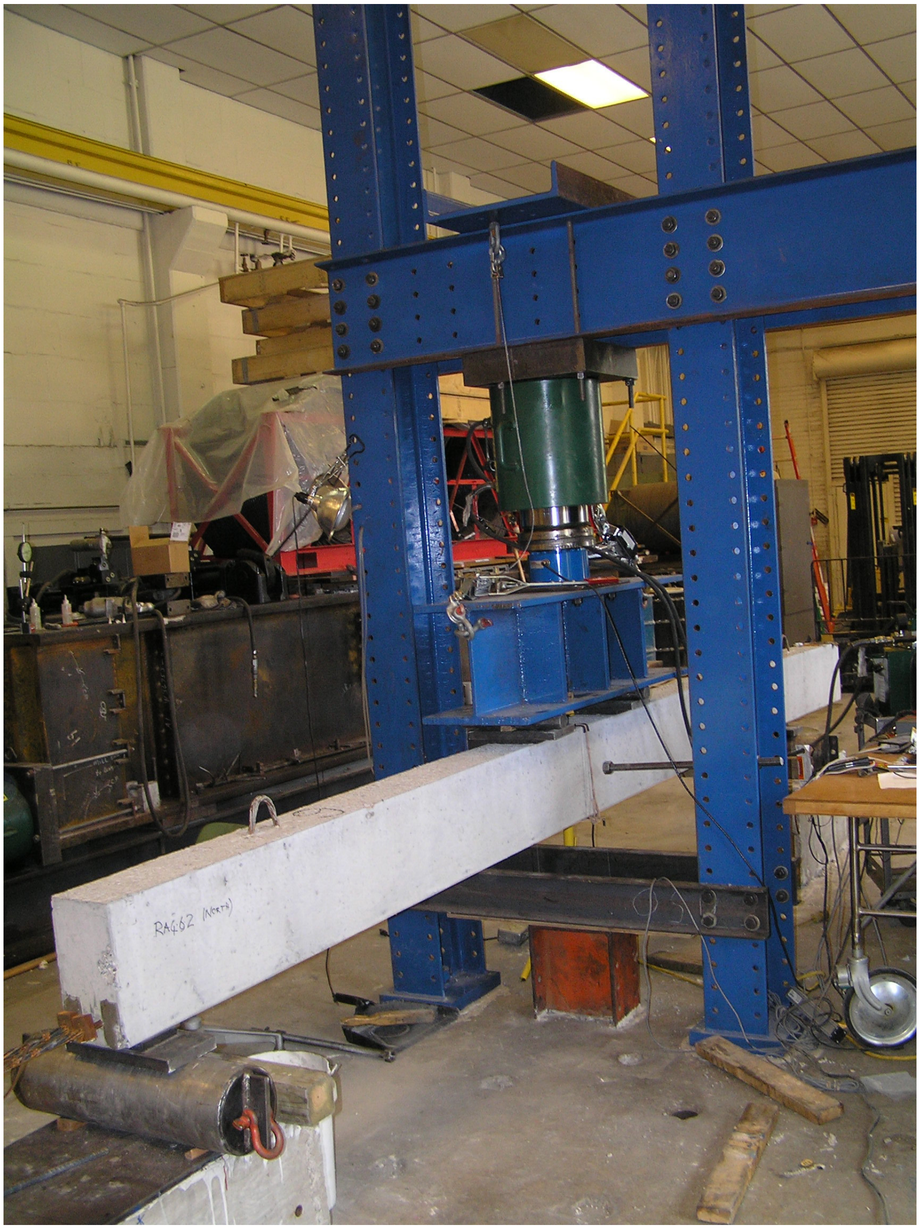

Figure 3.6: Test frame with one of the rectangular beams in place

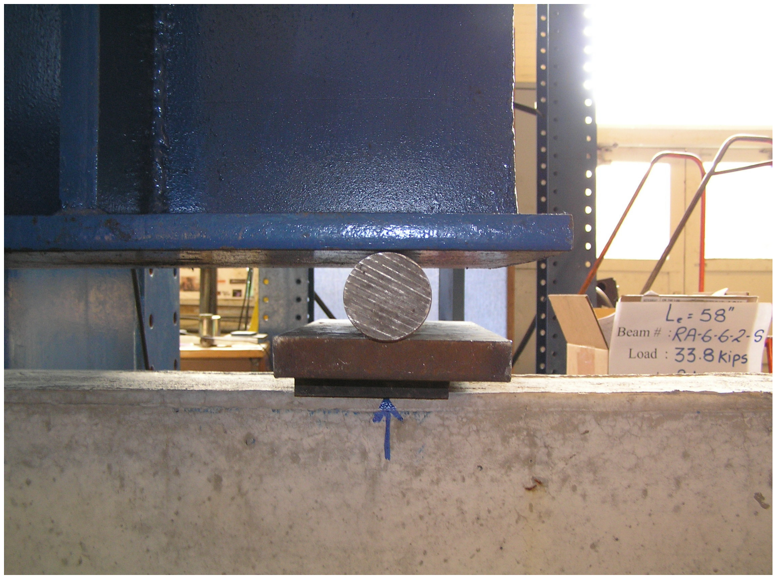

Figure 3.7: Photo showing a point load being applied at the required point using a steel roller

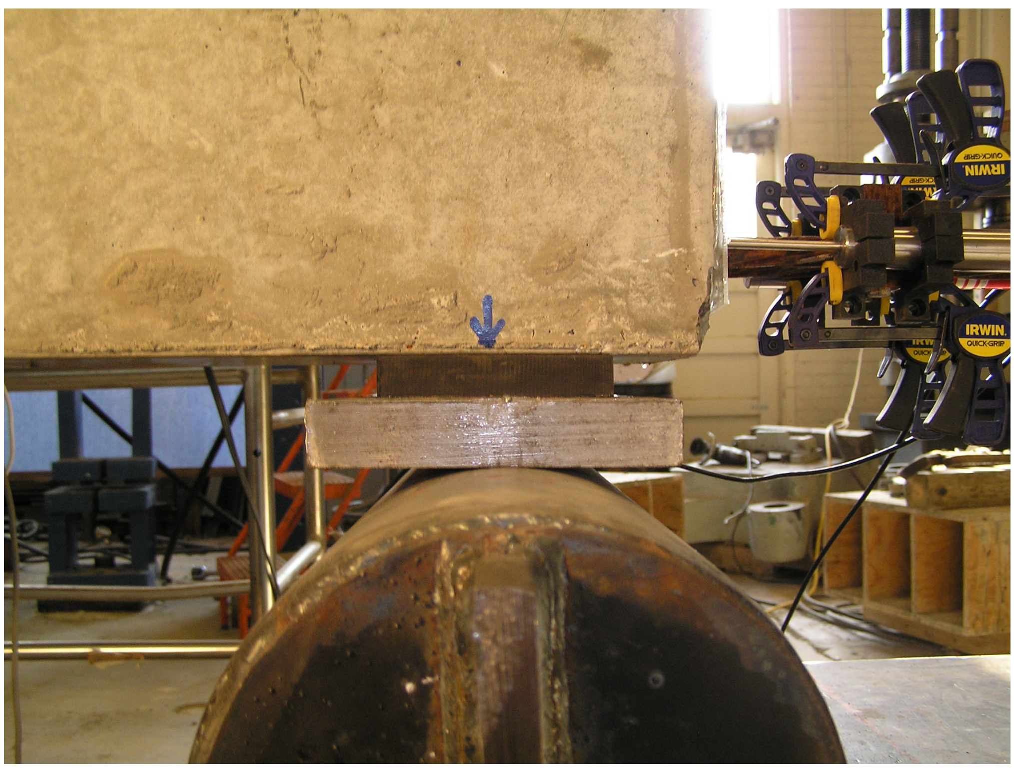

Figure 3.8: Photo showing a typical support (in this case – rectangular beam)

3.4 LOADING GEOMETRY

Both rectangular and I-shaped beams were designed to be tested on both ends enabling a possibility of two separate flexural tests per beam. To obtain two different sets of data, the embedment length was varied for the flexural test at two ends. Embedment lengths were changed as the testing progressed depending on the acquired results. In other words, the embedment length was adjusted based on results of the preceding tests.

3.4.1 Rectangular shaped beams

To ensure proper bearing conditions at the testing end, 4 in. distance was extended beyond the support for all rectangular beam tests unless the condition of the beam forced otherwise. Wherever this distance was changed, it was recorded along with the photograph clearly showing the necessity to do so. Typical loading geometry for the North ends included a 4 in. distance beyond the support and 69 in. distance between the points of support to the first point of loading. This provided an embedment length of 73 in. over which the strands were allowed to develop bond with concrete. Constant moment region for a typical setup was kept 24 inches. For the rectangular beams, exactly same distances were maintained on the other side of the testing end, giving a symmetrical loading condition. The total span thus was kept at 162 in. for typical North end testing. For typical South end testing, the distance beyond the support was maintained 4 in. while the distance between the support and the first load point was reduced to 54 in. providing an embedment length of 58 in. To obtain symmetric loading, equal distances were provided on the other side thus reducing the span to 132 in. Figure 3.9 shows the typical loading setup for the rectangular beams.

3.4.2 I-shaped beams

Owing to the higher capacities of the I-shaped beams as compared to the rectangular beams, higher reactions were expected at the supports. Distance beyond the support was thus increased to 6 in. for ensuring proper bearing conditions. Also since web shear cracks were expected, the embedment lengths were kept higher than those provided for the rectangular beams. As the embedment lengths were higher, the beam could not be loaded symmetrically within the available space. For this purpose, the loading geometry was so designed as to achieve a constant moment region between the two point loads even though the load frame was shifted nearer to the test end of the beam. Figure 3.10 shows a typical loading setup for I-shaped beams.

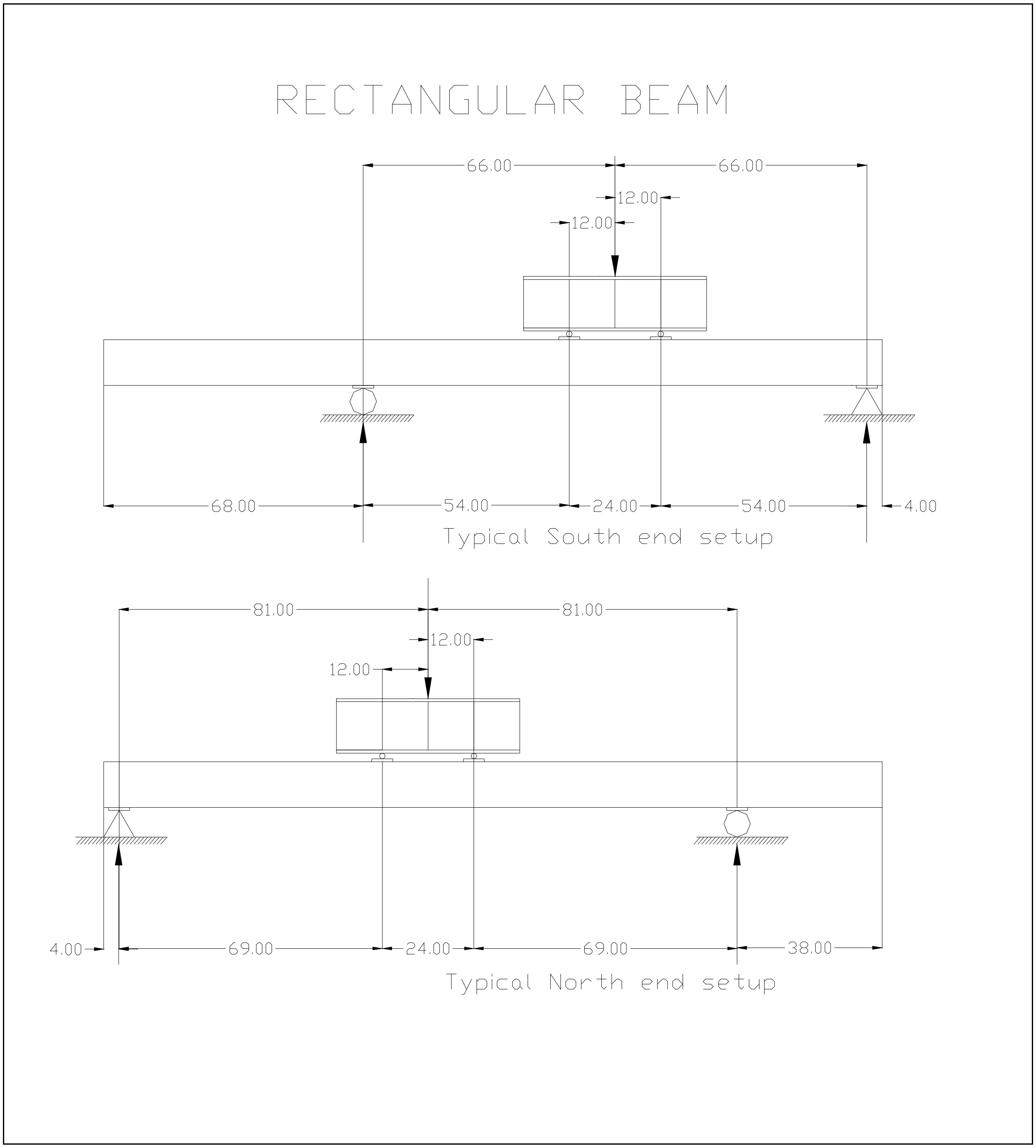

Figure 3.9: Typical loading geometry for rectangular beams

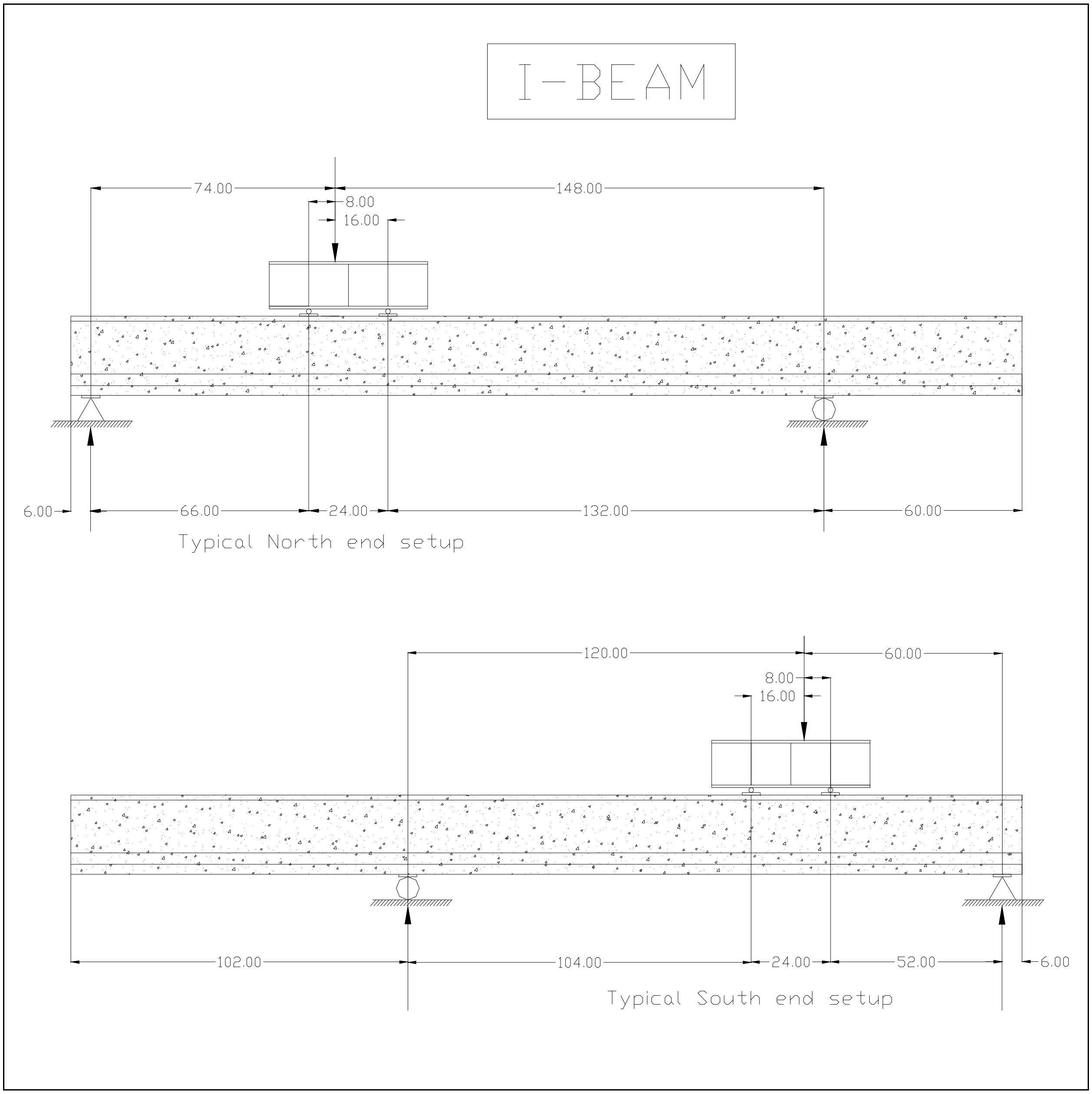

Figure 3.10: Typical loading geometry for I-shaped beams

3.5 INSTRUMENTATION

3.5.1 Load

Load was measured with a load cell placed between a spherical head under the hydraulic actuator and the spreader beam. Interface load cell (model #1200) was used which had a capacity of 100 kips; accuracy up to ±0.05 kips, and allowed limit of 50% overloading beyond its capacity.

3.5.2 Displacement

Wire transducers with a range of 30 in. and accuracy up to 0.005 in. were used to determine the deflection vertically below the center-line of the load cell. Two wire transducers were used to measure deflection on both sides of the beam for nullifying any variations due to torsion. Average value at a particular load was noted as displacement at that load. In addition to the electronic data, a dial gauge with a least count of 1000^{th} of an inch was used to note the readings manually which also served as a tool for displacement controlled loading.

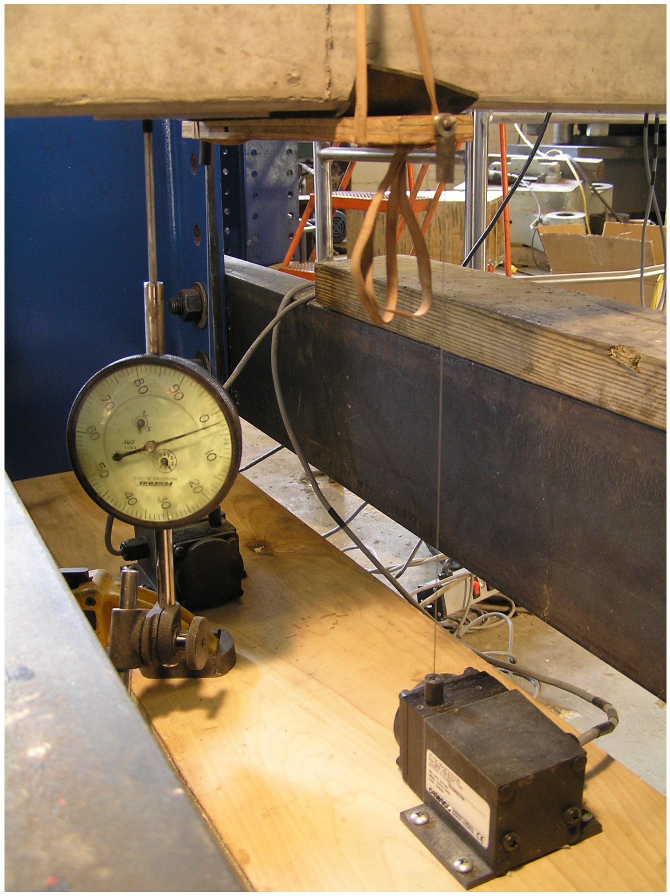

Figure 3.11: Setup for deflection measurement

3.5.3 End-slip

Linear voltage displacement transducers (LVDT) having 1 in. stroke were used to record the end-slips of the strands up to 1000th of an inch. Clamps were attached to the strands tightly and LVDTs were mounted on these clamps at a location providing initial reading of 0.9 in. with an unavoidable error of ± 3/1000th of an inch. As the strand slipped, the readings decreased and end slip was noted as the difference between final and initial readings. Rectangular beams required two LVDTs for east and west bottom strands. For I shaped beams, total of 4 LVDTs were required, one each for top, middle, bottom east and bottom west strands. Plexi-glass plates were glued to the concrete surface for providing a smooth surface for resting the tips of LVDTs.

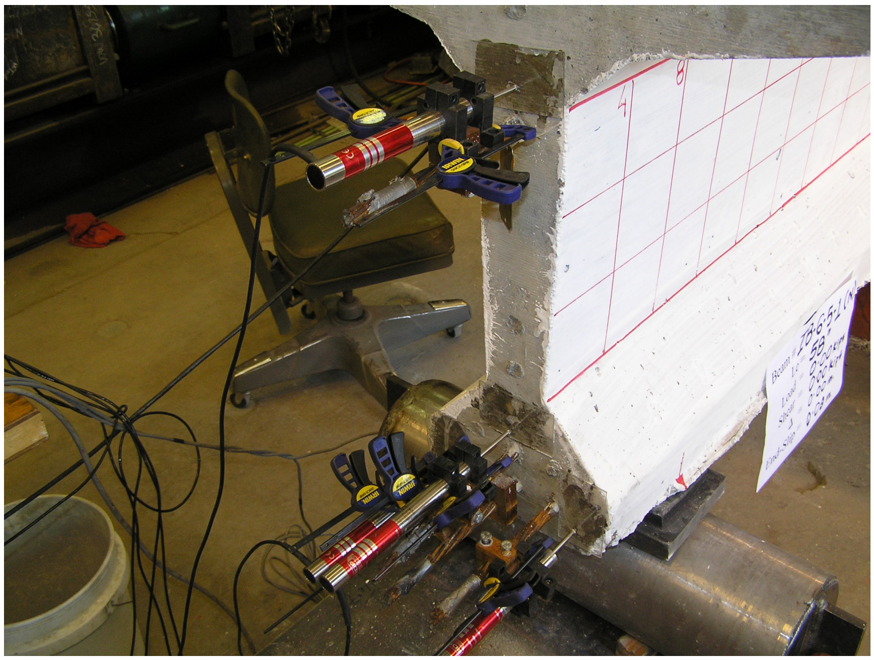

Figure 3.12: Photo showing LVDTs attached to the strands for one of the I-shaped beams

Figure 3.13: Photo showing digital dial gauge attached to the strands at the opposite end for one of the rectangular beams

3.5.4 Electronic data acquisition

Each of the electronic devices was connected to a single data acquisition system which transferred the data to a computer. Different devices were connected to different channels enabling proper calibration of each device and recording the data individually. The rate of sampling was fixed at 1 Hz which provided smooth transition of load, displacement and end-slip values. This stored data was used for producing moment vs. deflection and end-slip vs. deflection charts. Also, all individual values were displayed on the computer screen and were manually noted at every load/deflection increment.

3.5.5 Strain Measurements

For I shaped beams, average shear strain was measured with the help of DEMEC target points located in a rectangular strain rosette pattern on both sides of the beam. The center of the rectangular strain rosette was fixed at mid-height of the web and at 30 in. from the support point of the corresponding beam end. DEMEC readings were taken at each load/displacement increment and average shear strain was calculated using the formulae for the rectangular strain rosette pattern.

For rectangular shaped beams, strains were measured on the concrete surface at the level of strands and at 2 in. below the top surface of concrete. Four DEMEC points were glued to the concrete surface at linear distances of 10 cm. Values of strain on the concrete surface gave an idea of the strain in the embedded strands at the same level.

Figure 3.14 and Figure 3.15 shows the arrangements of DEMEC points on the surface of I-shaped beams and rectangular beams respectively.

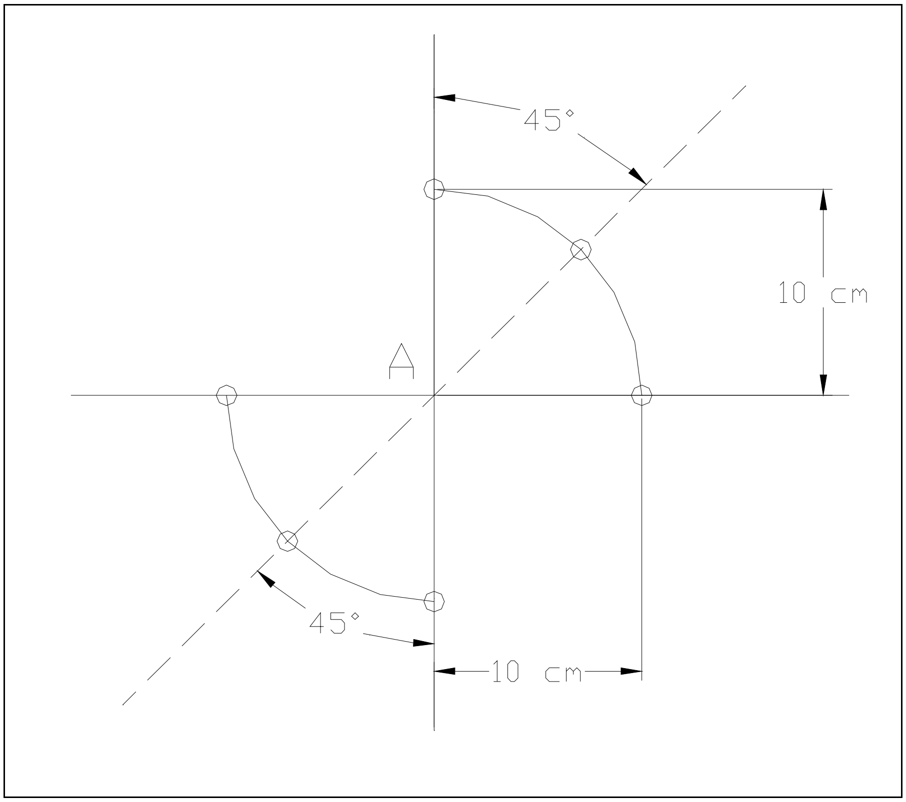

Figure 3.14: Diagram of rectangular rosette pattern on I-beams

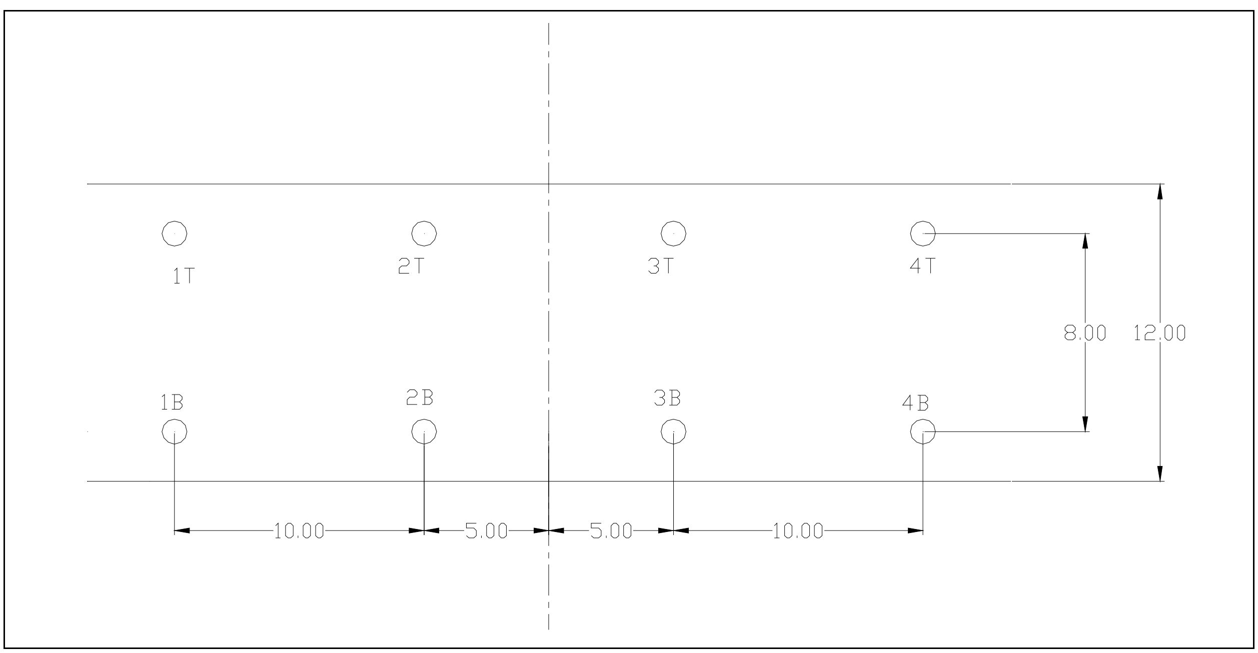

Figure 3.15: Diagram showing arrangement of DEMEC points on the surface of rectangular beams (dimensions shown are in cm.)

3.6 PROCEDURE

Rectangular and I-shaped beam specimens were being transported from the Core Slab structures in Oklahoma City to Oklahoma State University once they were ready to be tested. Care was taken for ensuring that concrete had gained almost its full design strength by allowing a time span of more than 56 days before they were moved. All the beams were placed on 4” x 4” timber sections kept approximately 4 feet from the ends to avoid direct contact of the ground on the bottom surface of concrete. Once at Oklahoma State University, the beams were stored in open till the day of testing.

On the day of testing, the concrete blocks on which the support roller rested, were moved at appropriate locations depending on the loading span. Both the support rollers were ensured to be in level with the help of a clear tube containing water. Support roller at the testing end was fixed by wedges to serve as a pin support. Other roller was left free to rotate and thus provided a roller support. Steel plates and neoprene pads were kept in position on top of the support rollers.

The support load point locations were marked on the beam specimen as pointed arrows. Each beam was being lifted with the help of a fork lift and a gantry crane and placed gently on the support rollers so that the arrow markings coincided with the topmost point of the roller. The support beam was lowered on the beam with top rollers coinciding with the load point locations marked on the beam. The geometry of load points and support locations was once again checked for accuracy.

End slip readings were noted for determining the corresponding transfer lengths at the day of testing. For the I-shaped beams the sides were painted white at least up to a distance of 110 in. from the testing end. Also, in case of I-shaped beams and a selected few rectangular beams, the DEMEC target points were attached at predetermined locations on the web of the beams. LVDTs were attached to the strands and were set to initial reading of approximately 0.9 in. An electronic dial gauge was fixed on one of the strands at the opposite end for recording any end slip at that end. The tips of wire transducers were connected to the bottom surface of the beams vertically aligned with the center line of the hydraulic actuator. Before loading, initial readings for load, displacement, end slip and in case of I-shaped beams DEMEC readings were noted.

Load increments were determined by the response of the beam, so as to obtain predetermined deflection increments up to first flexural cracking. Beyond this point displacement control was used to apply further increments. Loading was continued till failure or till the beam could not maintain the load. At all load increments, values of load, displacement, end slips and DEMEC readings (wherever applicable) were noted. Cracks were marked with permanent markers as soon as they were observed. The loads at which the cracks first appeared were mentioned along side of the cracks. Photographs were taken at regular intervals to keep track of crack patterns.

Electronic readings of load, displacement, end slips were transferred to the computer with the help of data acquisition system and stored for future use. Throughout the test, manual readings at every load increment were noted along with any significant observation such as first flexural crack, first shear crack, appearance of flexure-shear crack, first end slip, concrete spalling, concrete crushing and any audible observations.

Plots of moment vs. deflection, end-slip vs. deflection and shear vs. average shear strain were plotted from the acquired data. Detailed progress of each test was documented and is included along with significant photographs and data plots in Appendices A – E.

CHAPTER IV

4.0 PRESENTATION OF EXPERIMENTAL RESULTS

4.1 INTRODUCTION

Altogether 50 flexural tests were performed on rectangular beams and 14 tests on I-shaped beams. All of these tests were carried out at the Civil Engineering Laboratory at Oklahoma State University. Most of the beams were tested on both ends. For each beam test, the embedment length was determined based on various factors including the AASHTO development length equation with changes to account for prior results, concrete strength or strand bond strength.

4.2 TABULTED BEAM TEST RESULTS

In the following section, tables are provided to compare the test results of rectangular beams and I-shaped beams. These tables include concrete strengths at release and at 56 days, average NASP value for the strands used, embedment length, loading span, maximum applied moment, percentage of nominal capacity attained, maximum deflection, maximum end slip and the classification of type of failure, for each beam tested. Table 4.1 through Table 4.3 provides test parameters for rectangular tests, while Table 4.4 and Table 4.5 provide the same for I-beams.

The terminology used to describe the type of failure of each beam is explained in section 4.3. Detailed beam summaries along with moment-deflection, end-slip vs. deflection and shear vs. average shear strain charts and photographs taken during the test are included in Appendices A-E.

Table 4.1: Flexural test results for rectangular beams with Strand D (0.5 in.)

Beam End	fc' RLS	fc' 56 days	Average NASP P.O Value	Average Lt @ RLS	Average Lt (56 day or @ test)	Actual Le	Span	Failure Moment	%Mn	Deflection @ Failure	Max. End-Slip	Failure Mode
	(psi)	(psi)	(lbs.)	(in.)	(in.)	(in.)	(in.)	(kip-in)	(%)	(in.)	(in.)	
RD-4-5-1-N	4033	7050	6890	32.79	38.54	73	162	804	115%	3.4	0.00	Flexural
RD-4-5-1-S	4033	7050	6890	31.02	42.28	58	132	759	108%	1.6	0.35	Bond
RD-4-5-2-N	4033	7050	6890	42.19	63.05	73	162	831	119%	2.7	0.40	Flexural
RD-4-5-2-S	4033	7050	6890	49.71	51.81	58	132	513	73%	2.5	0.57	Bond
RD-6-5-1-N	6183	8500	6890	30.24	49.75	73	162	797	111%	2.5	0.06	Flexural
RD-6-5-1-S	6183	8500	6890	28.07	45.26	58	132	788	109%	2.0	0.18	Flexural
RD-6-5-2-N	6183	8500	6890	25.60	44.24	73	162	735	102%	2.0	0.01	Flexural
RD-6-5-2-S	6183	8500	6890	29.22	48.27	58	132	724	100%	2.0	0.25	Bond
RD-6A-5-1-N	7960	11420	6890	35.4	39.94	73	162	794	106%	2.3	0.00	Flexural
RD-6A-5-1-S	7960	11420	6890	29.1	37.16	58	132	805	108%	2.5	0.08	Flexural
RD-6A-5-2-N	7960	11420	6890	20.48	32.39	73	162	780	104%	3.0	0.00	Flexural

Beam End	fc' RLS	fc' 56 days	Average NASP P.O Value	Average Lt @ RLS	Average Lt (56 day or @ test)	Actual Le	Span	Failure Moment	%Mn	Deflection @ Failure	Max. End-Slip	Failure Mode
	(psi)	(psi)	(lbs.)	(in.)	(in.)	(in.)	(in.)	(kip-in)	(%)	(in.)	(in.)	
RD-6A-5-2-S	7960	11420	6890	20.08	40.07	58	132	778	104%	1.9	0.02	Flexural
RD-8-5-1-N	8570	13490	6890	20.15	39.08	73	162	811	107%	2.6	0.00	Flexural
RD-8-5-1-S	8570	13490	6890	20.15	34.54	58	132	805	106%	2.6	0.08	Flexural
RD-8-5-2-N	8570	13490	6890	13.67	37.38	58	132	775	102%	2.2	0.08	Flexural
RD-8-5-2-S	8570	13490	6890	17.30	50.41	58	132	813	107%	2.0	0.00	Flexural
RD-10-5-1-N	9711	14470	6890	26	30.24	58	132	821	108%	2.1	0.00	Flexural
RD-10-5-1-S	9711	14470	6890	13.57	27.14	46	120	819	107%	2.6	0.00	Flexural
RD-10-5-2-N	9711	14470	6890	14.85	22.30	58	132	788	103%	1.9	0.00	Flexural
RD-10-5-2-S	9711	14470	6890	18.23	22.03	46	120	794	104%	1.9	0.01	Flexural

Table 4.2: **Flexural test results for rectangular beams with Strand A/B (0.5 in.)**

Beam End	fc' RLS	fc' 56 days	Average NASP P.O Value	Average Lt @ RLS	Average Lt (56 day or @ test)	Actual Le	Span	Failure Moment	%Mn	Deflection @ Failure	Max. End-Slip	Failure Mode
	(psi)	(psi)	(lbs.)	(in.)	(in.)	(in.)	(in.)	(kip-in)	(%)	(in.)	(in.)	
RA-6-5-1-N	6183	8500	20950	19.2	33.70	73	162	790	110%	2.1	0.00	Flexural
RA-6-5-1-S	6183	8500	20950	18.2	30.03	58	132	800	111%	2.1	0.00	Flexural
RA-6-5-2-N	6183	8500	20950	16.5	28.00	58	120	772	107%	1.5	0.00	Flexural
RA-6-5-2-S	6183	8500	20950	15.01	23.50	46	120	777	108%	1.5	0.00	Flexural
RA-6A-5-1-N	7960	11420	20950	17.74	26.54	73	162	769	103%	2.4	0.00	Flexural
RA-6A-5-1-S	7960	11420	20950	17.68	28.55	58	132	770	103%	1.7	0.00	Flexural
RA-6A-5-2-N	7960	11420	20950	24.51	31.75	58	132	788	105%	1.9	0.00	Flexural
RA-6A-5-2-S	7960	11420	20950	22.03	29.38	46	120	788	105%	1.7	0.01	Flexure
RA-8-5-1-N	8570	13490	20950	13.3	24.91	58	132	829	109%	1.7	0.01	Flexural
RA-8-5-1-S	8570	13490	20950	13.5	22.54	46	120	832	110%	1.9	0.00	Flexural
RA-10-5-1-N	9711	14470	20950	24.27	24.34	58	132	788	103%	1.7	0.00	Flexural

Beam End	fc' RLS	fc' 56 days	Average NASP P.O Value	Average Lt @ RLS	Average Lt (56 day or @ test)	Actual Le	Span	Failure Moment	%Mn	Deflection @ Failure	Max. End-Slip	Failure Mode
	(psi)	(psi)	(lbs.)	(in.)	(in.)	(in.)	(in.)	(kip-in)	(%)	(in.)	(in.)	
RA-10-5-1-S	9711	14470	20950	9.69	13.14	46	120	796	104%	1.7	0.00	Flexural
RB-4-5-1-N	4033	7050	20210	18.42	22.10	73	162	776	111%	1.9	0.00	Flexural
RB-4-5-1-S	4033	7050	20210	18.49	20.51	58	132	802	114%	2.0	0.00	Flexural
RB-4-5-2-N	4033	7050	20210	21.12	22.52	73	162	721	103%	2.4	0.00	Flexural
RB-4-5-2-S	4033	7050	20210	22.46	23.75	58	132	748	107%	1.7	0.00	Flexural

Table 4.3: Flexural test results for rectangular beams with Strand A (0.6 in.)

Beam End	fc' RLS	fc' 56 days	Average NASP P.O Value	Average Lt @ RLS	Average Lt (56 day or @ test)	Actual Le	Span	Failure Moment	%Mn	Deflection @ Failure	Max. End-Slip	Failure Mode
	(psi)	(psi)	(lbs.)	(in.)	(in.)	(in.)	(in.)	(kip-in)	(%)	(in.)	(in.)	
RA-4-6-1-N	4033	7050	18290	33.42	41.82	88	192	1084	114%	3.0	0.00	Flexural
RA-4-6-1-S	4033	7050	18290	24.96	28.87	70	156	964	102%	2.7	0.00	Flexural
RA-4-6-2-N	4033	7050	18290	30.24	37.66	73	162	1011	107%	2.4	0.13	Flexural
RA-4-6-2-S	4033	7050	18290	29.35	33.19	58	148	921	97%	3.0	0.33	Bond
RA-6-6-1-N	4855	8040	18290	29.73	40.85	88	192	1012	104%	2.5	0.00	Flexure
RA-6-6-2-N	4855	8040	18290	31.65	52.18	73	162	1001	103%	2.1	0.02	Flexure
RA-6-6-2-S	4855	8040	18290	30.1	49.37	58	148	913	94%	2.7	0.41	Bond
RA-6-6-3-N	4855	8040	18290	25.83	44.96	88	192	1046	108%	2.6	0.00	Flexure
RA-8-6-1-N	5413	8220	18290	28.21	45.48	88	192	1008	103%	2.4	0.00	Flexure
RA-8-6-2-N	5413	8220	18290	28.2	46.35	73	162	1007	103%	2.0	0.01	Flexure
RA-8-6-2-S	5413	8220	18290	25.7	42.37	58	132	988	~101%	2.5	0.14	Bond

Beam End	fc' RLS	fc' 56 days	Average NASP P.O Value	Average Lt @ RLS	Average Lt (56 day or @ test)	Actual Le	Span	Failure Moment	%Mn	Deflection @ Failure	Max. End-Slip	Failure Mode
	(psi)	(psi)	(lbs.)	(in.)	(in.)	(in.)	(in.)	(kip-in)	(%)	(in.)	(in.)	
RA-10-6-1-N	9150	14610	18290	20.03	29.98	88	192	1084	102%	2.8	0.00	Flexure
RA-10-6-2-N	9150	14610	18290	15.62	26.79	73	162	1070	101%	2.5	0.00	Flexure
RA-10-6-2-S	9150	14610	18290	21.78	30.70	58	148	1083	102%	2.4	0.00	Flexure

Table 4.4: Flexural Test Results – I-Shaped beams (0.5 in Strands)

Beam End	Measured overall depth (h)	fc' RLS	fc' 56 days	Average NASP P.O Value	Le	Span	Maximum Moment	%Mn	Maximum Deflection	Max. End-Slip	Failure Mode
	(in.)	(psi)	(psi)	(lbs.)	(in.)	(in.)	(kip-in)	(%)	(in.)	(in.)	
IB-6-5-1-N	24	5810	9350	20210	52	166	3526	82%	1.1	0.04	No Failure
IB-6-5-1-S	24	5810	9350	20210	72	222	3980	98%	3.1	0.03	Flexure
IB-10-5-1-N	24	7615	13490	20210	54	168	4282	98%	2.0	0.03	No Failure
IB-10-5-1-S	24	7615	13490	20210	58	180	4196	100%	1.6	0.02	No Failure

Beam End	Measured overall depth (h)	fc' RLS	fc' 56 days	Average NASP P.O Value	Le	Span	Maximum Moment	%Mn	Maximum Deflection	Max. End-Slip	Failure Mode
	(in.)	(psi)	(psi)	(lbs.)	(in.)	(in.)	(kip-in)	(%)	(in.)	(in.)	
ID-6-5-1-N	24	5492	9840	6890	72	222	3538	82%	2.5	0.80	Bond
ID-6-5-1-S	24	5492	9840	6890	88	270	3280	81%	3.5	0.75	Bond
ID-10-5-1-N	24	8225	14160	6890	88	270	4026	92%	5.2	0.01	No Failure
ID-10-5-1-S	24	8225	14160	6890	72	222	4039	96%	3.7	0.75	Bond

Table 4.5: Flexural Test Results – I-Shaped beams (0.6 in Strands)

Beam End	Measured overall depth (h)	fc' RLS	fc' 56 days	Average NASP P.O Value	Le	Span	Maximum Moment	%Mn	Maximum Deflection	Max. End-Slip	Failure Mode
	(in.)	(psi)	(psi)	(lbs.)	(in.)	(in.)	(kip-in)	(%)	(in.)	(in.)	
IA-6-6-1-N	24.125	4381	8990	18290	75	156	3267	69%	1.7	0.05	Shear @ opposite end
IA-6-6-1-S	24.125	4381	8990	18290	91	188	4387	99%	2.8	0.12	Flexure

Beam End	Measured overall depth (h)	fc' RLS	fc' 56 days	Average NASP P.O Value	Le	Span	Maximum Moment	%Mn	Maximum Deflection	Max. End-Slip	Failure Mode
	(in.)	(psi)	(psi)	(lbs.)	(in.)	(in.)	(kip-in)	(%)	(in.)	(in.)	
IA-6-6-2-N	24.125	4381	8990	18290	88	270	4125	87%	3.2	0.13	Shear
IA-10-6-1-N	24.25	10480	14990	18290	58	166	4243	87%	1.2	0.05	Shear @ opposite end
IA-10-6-1-S	24.25	10480	14990	18290	72	222	4620	101%	2.5	0.03	Strand Facture
IA-10-6-2-N	24.375	10590	14930	18290	72	222	2983	61%	0.9	0.00	Shear @ opposite end
IA-10-6-2-S	24.375	10590	14930	18290	88	270	4559	99%	5.7	0.00	Flexure

4.3 TYPES OF FAILURES

During the flexural tests on rectangular and I-shaped beams, certain terminology was used to describe the end point of test or failure of the beam. Following failure modes were observed (i) Flexural failure (ii) Bond failure (iii) Shear failure. For the beams which did not fall in any of these 3 categories, the end points of the test was mentioned as (a) Failure did not occur or (b) Shear failure at the opposite end. This section explains the criteria on how the failure modes were determined. Also, a typical example from each particular failure mode is described. Parameters such as the failure moment, or actual test moment achieved, maximum applied shear force, the type and extent of cracking, and the maximum end slip characteristics were used to classify the type of beam test result into one of the above mentioned modes.

4.3.1 Flexural failure

Beam specimens were said to have failed in flexure when;

1. The applied moment matched, nearly matched or exceeded the nominal moment capacity, Mn, of the beam as calculated from strain compatibility; and

2. The beam displayed the ability to sustain moment resisting capacity despite large deformations.

For strain compatibility calculations, the maximum strain in concrete was estimated at 0.003 in./in.

Failure of the beam specimen was typically characterized by the crushing of the top surface of concrete mostly in the constant moment regions. Beam specimen that failed in flexure also showed considerable ductility with values of deflection increasing gradually with the sustained loads. In some flexural failures, strand fractures occurred. Typically strand fractures occurred in beams made with higher strength concrete. Such failures did not demonstrate crushing of concrete at the top surface, yet the applied moments were high enough to cause tensile failure of the strands.

<u>Typical example of flexural failure in rectangular Beams</u>

Name of the beam:RB-4-5-1

End of the beam tested: SOUTH

Test Date: 07/20/2005

Table 4.6: Test Parameters for South end of the beam RB-4-5-1

TEST PARAMETERS	
Concrete Compressive Strength	**7050 psi**
Embedment Length(L_e)	**58 in.**
Span	**132 in.**
Failure Mode	**Flexure**
Maximum Load	**29.7 kips**
Maximum Moment	**980 kip-in**
Deflection @ Failure	**2.0 in.**
Rebound after complete unloading	**1.6 in.**
Average Transfer Length (L_t) @ release	**18.5 in.**
@ time of testing	**20.5 in.**
Average NASP P.O value for strand "B"	**20.21 kips**

Test Highlights

Flexural cracks were first formed at 18.6 kips and at the deflection of 0.4 in. These cracks were located at the mid-span region where maximum moments were constant between load points. The cracks originated at the bottom surface and propagated vertically upwards. Strand end slip readings remained 0.00 in. while the load increased with increasing deflections. As the load value reached 29.7 kips and at deflection of 2.0 in., concrete crushing was noticed at the top surface in the constant moment region. Moment at this stage was 112% of calculated nominal capacity.

Failure of the beam was classified as flexural failure since applied moment matched or exceeded the calculated nominal capacity, Mn, of the beam. In this case, strand end slips remained zero even as the concrete crushing failure occurred. Result of this beam test suggests that the strand had developed adequate anchorage in the provided development length of 58 in.

Figure 4.1 shows the variation of Moment and end-slip with deflection. Figure 4.2 presents a photograph of the crushed concrete.

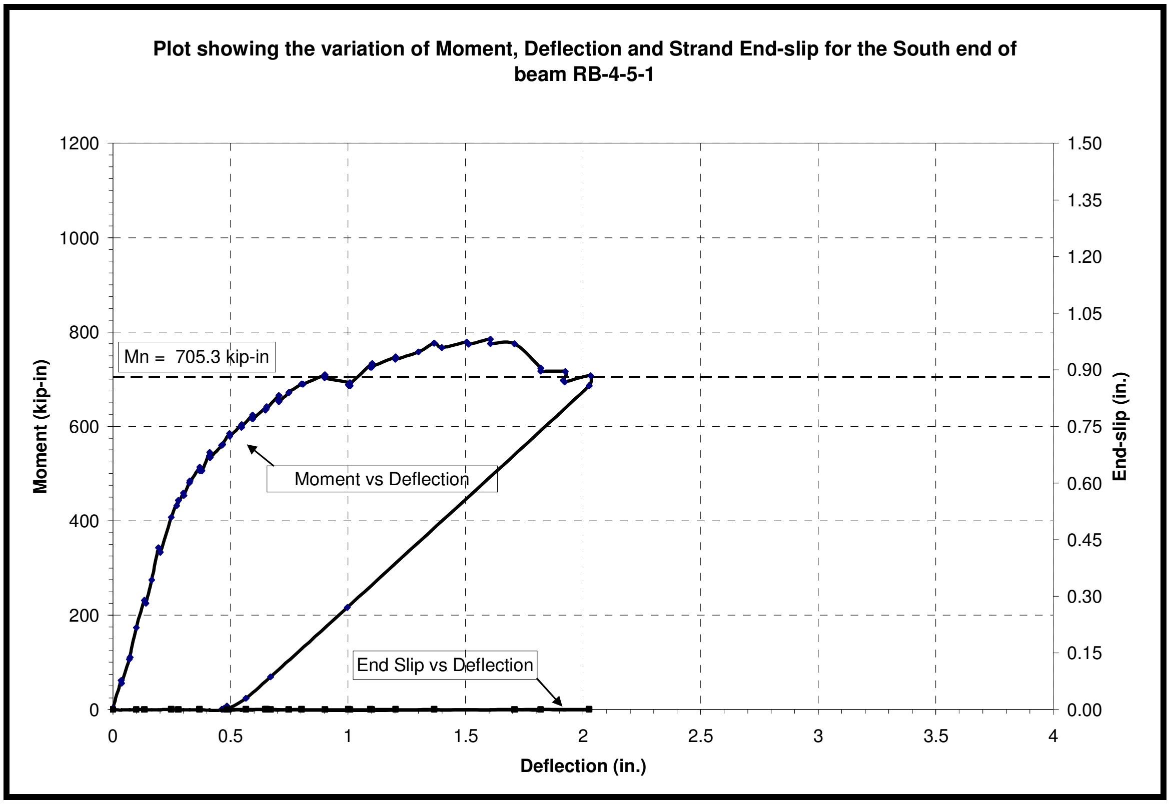

Figure 4.1: Moment –Deflection curve with end-slips for South end of the beam RB-4-5-1

Figure 4.2: Concrete crushing at the top surface of concrete (Test – RB-4-5-1 S)

Typical example of flexural failure in I-shaped beams

Name of the beam : IA-10-6-1

End of the beam tested: SOUTH

Test Date: 10/26/2005

Table 4.7 : Test parameters for South end of the beam IA-10-6-1

TEST PARAMETERS	
Concrete Compressive Strength	**14990 psi**
Embedment Length(L_e)	**72 in.**
Span	**222 in.**
Failure Mode	**Strand Fracture**
Maximum Load	**105 kips**
Maximum Shear	**70 kips**
Maximum Moment	**4620 kip-in.**
Maximum Deflection attained	**2.5 in.**
Average NASP P.O value for strand "A"	**18.29 kips**

Table 4.8 : Transfer length data for beam IA-10-6-1

	Transfer lengths (in.) for beam # IA-10-6-1		
		At Release	At the time of testing
SOUTH	Top	1.91	1.78
	Middle	-	-
	Bottom East	21.15	20.78
	Bottom Central	18.85	18.85
	Bottom West	5.81	5.2

Test Highlights

The beam first cracked in flexure at the load of 65.7 kips (Shear = 43.8 kips) and at a deflection of 0.33in. Strand end slip reading remained unchanged at first flexural cracking. The beam displayed first inclined flexural cracking at the load of 80.6 kips (Shear = 53.7 kips) and at deflection of 0.5 in. An inclined flexural crack is the one which originates as a flexural crack, starting vertically upwards from the bottom surface and then propagates at an angle as it reaches the web of the beam which is thinner as compared to the bottom bulb. The first web shear cracks were observed at a slightly higher load of 81.6 kips (Shear = 54.4 kips) and at a deflection of 0.58 in. A sudden drop in load was observed along with the first web shear cracking with load dropping down to 77.2 kips. A number of cracks were formed as web shear cracks. It was observed that these cracks formed at an inclined angle through the shear span on the South end, or "test" end of the beam. Although first shear cracking occurred at 81.6 kips, the first strand slip of 0.01 in., was observed at the load of 92.7 kips (Shear = 61.8 kips) and deflection of 0.9 in. As the loading continued, end slip reading increased gradually at a slow rate till it reached its maximum value of 0.03 in. The maximum load sustained by the beam was 105 kips (Max. Shear = 70 kips) and this load was reached at the deflection of 2.5 in. As the applied load increased from 92.7 kips to 105 kips, the beam deflection was increased from 0.9 in. to 2.5 in. which gives an idea about the ductility of the beam. At this maximum load, a loud noise was heard as the load dropped down to 94 kips. Examination of the test specimen showed that the Bottom East strand had fractured.

It is interesting to note that, in a beam where 0.03 in. of strand slip occurred, the beam failed by strand fracture. This result demonstrates that strand slip can occur in strands and in beams where the strands are able to develop the stress required for the beam to achieve nominal flexural capacity. Failure of beam occurred due to fracture of strand, where the attained maximum moment was greater than the nominal capacity. Accordingly, the failure was classified as flexural failure.

Figure 4.3 shows the variation of moment, deflection and the strand end slip during the test on South end of the beam IA-10-6-1. The sudden drop in load at strand fracture can be clearly seen from the graph. Figure 4.4 shows the variation of shear vs. average shear strain measured on the web of the beam at Station 36 from the South end. Figure 4.5 displays a photograph taken as the first web shear cracking occurred. Also, Figure 4.6 shows a photograph of the South end of the beam just after strand fracture occurred. In Figure 4.7 we can clearly see the fractured strand.

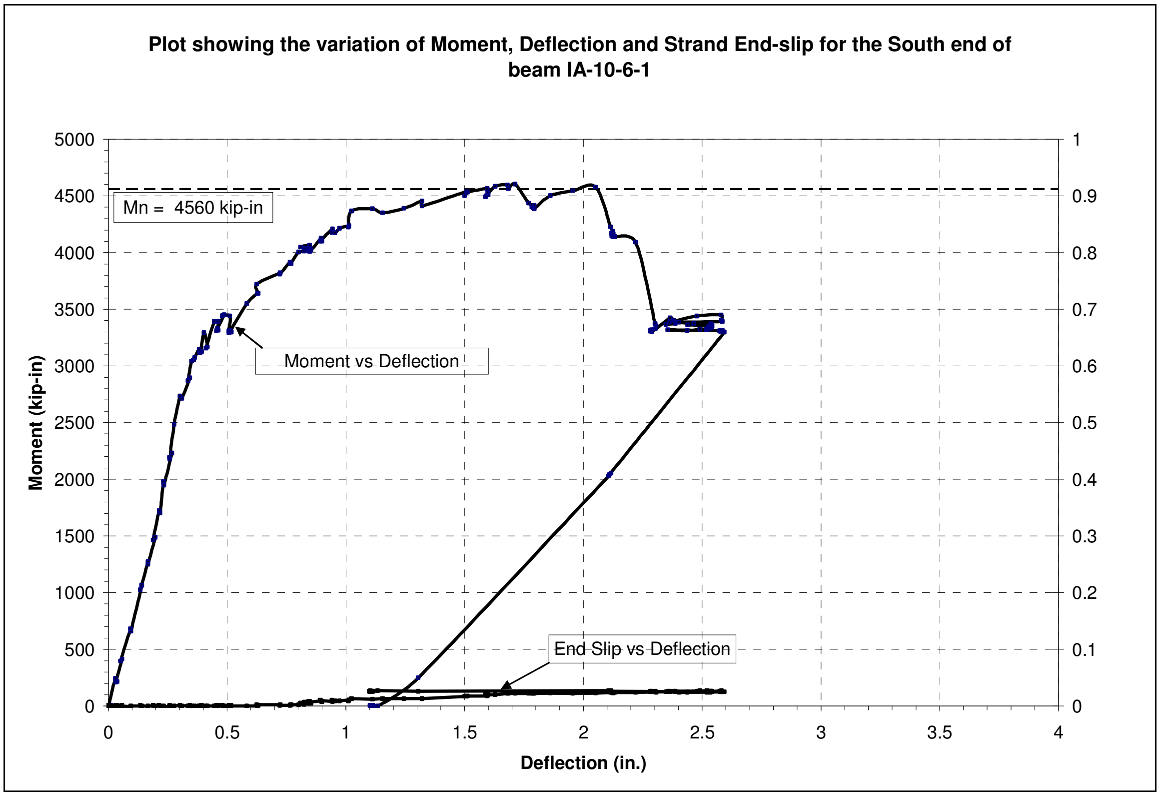

Figure 4.3: Photo of the South end of the beam IA-10-6-1 showing the first web shear cracking

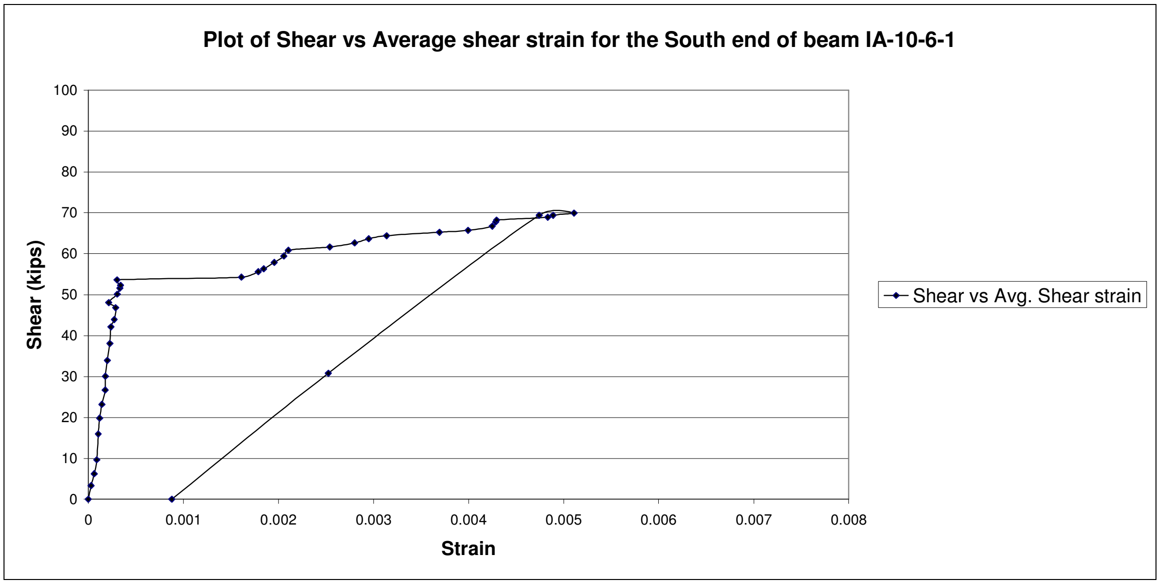

Figure 4.4 : Plot showing Shear vs Average shear strain for the South end of the beam IA-10-6-1

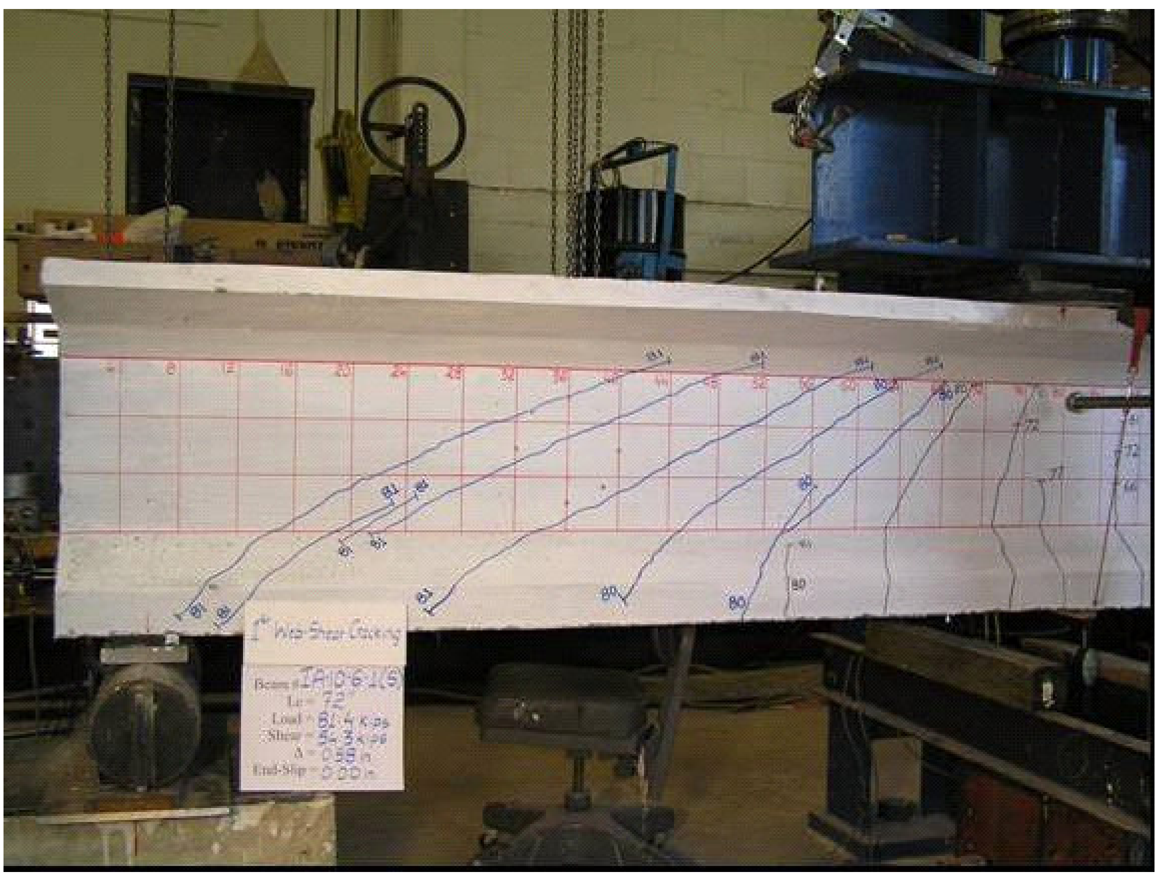

Figure 4.5: Photo showing the first web shear cracking on the South end of the beam IA-10-6-1

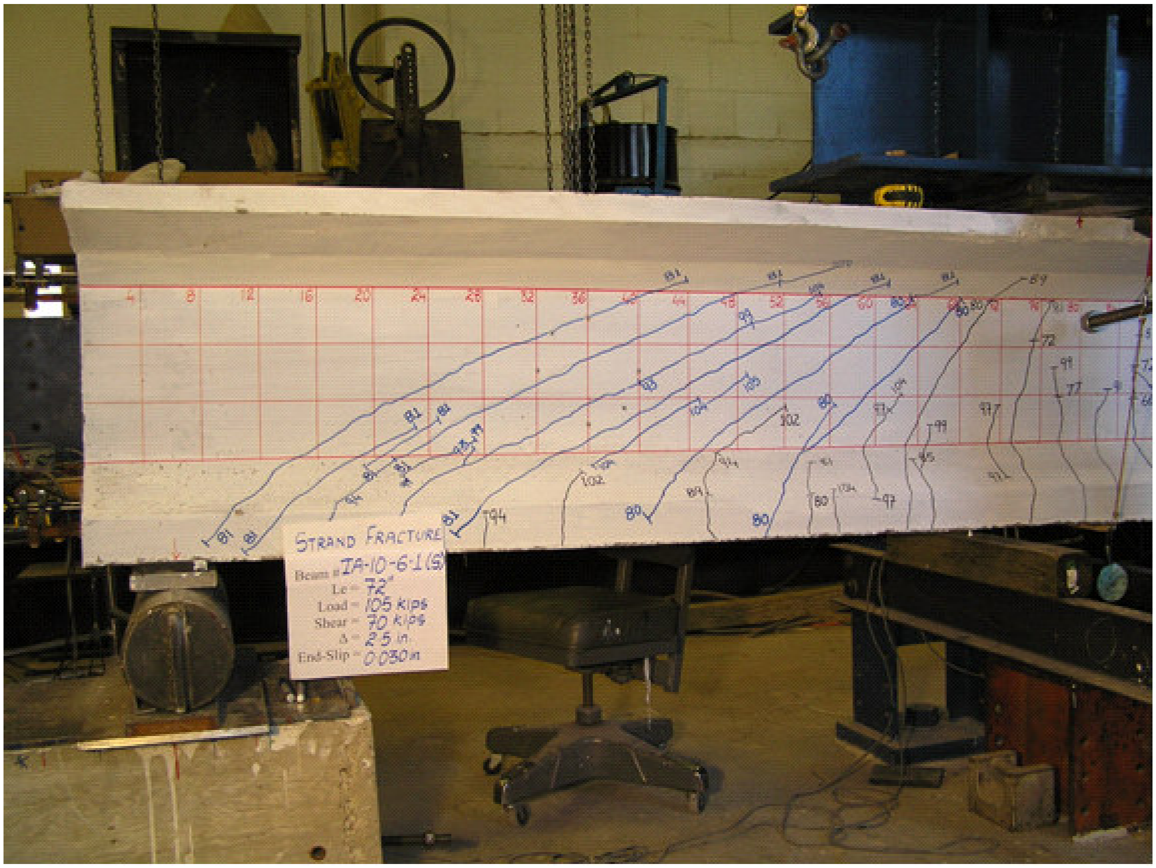

Figure 4.6: Photo of South end of beam IA-10-6-1 showing the cracking pattern at strand fracture

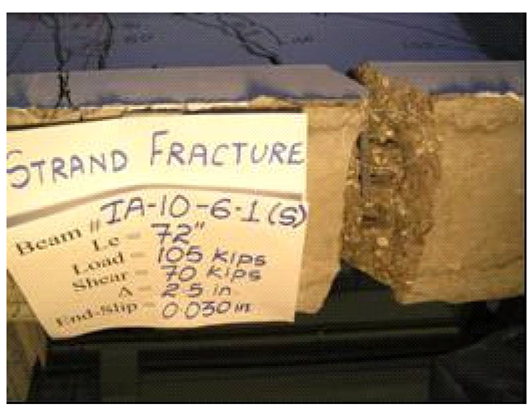

Figure 4.7: Photo showing the fractured strand (Test : IA-10-6-1-S)

4.3.2 Bond Failure

Bond failures are characterized typically by:

1. Excessive strand slips at the end of the beam; and
2. An inability displayed by the beam to achieve nominal flexural capacity.

Oftentimes, though not always, bond failures can be abrupt, sudden and occur without warning. However, it is generally noted that beam failing in bond demonstrate some measure of ductility, that is an ability to sustain load through large deformations, albeit at loads less than the calculated nominal capacity. In this series of tests, as in most series of development length tests, bond failures achieve relatively large capacities in comparison with their nominal flexural capacities.

Typical example of Bond Failure in Rectangular Beams

Name of the Beam: RD-4-5-2

End of the beam tested: SOUTH

Test Date: 07/25/2005

Table 4.9: Test Parameters for the South end o the beam RD-4-5-2

TEST PARAMETERS	
Concrete Compressive Strength	**7050 psi**
Embedment Length(L_e)	**58 in.**
Span	**132 in.**
Failure Mode	**Bond Failure**
Maximum Load	**19 kips**
Maximum Moment	**513 kip-in**
Deflection @ Failure	**2.5 in.**
Rebound after complete unloading	**1.7 in.**
Average Transfer Length (L_t) @ release	**49.7 in.**
@ time of testing	**51.8 in.**
Average NASP P.O value for strand "D"	**6.89 kips**

Test Highlights

Initial flexural cracking was observed at the load of 11.4 kips and deflection of 0.2 in. At this stage, a single crack was observed in the mid-span region. An inclined flexural crack was noticed at the load of 16 kips and deflection of 0.3 in. This inclined flexural crack grew in width as the load increased while other flexural cracks did not show such significant widening. First instance of strand slipping at the ends by 0.01 in. was noticed at the load of 18.2 kips and deflection of 0.5 in. The value of end slip continued to increase with further load increments. As the inclined flexural crack reached the top surface of the beam, a sudden jerk was observed with crushing of part of the surface near the tip of inclined flexural crack. The end slip reading had attained the value of 0.57 in. at this stage and the moment was still only 72% of the nominal strength as calculated using the ACI 318-02 method.

Failure of the beam was classified as Bond Failure as the value of end slip was large and the maximum moment attained was significantly less than the nominal capacity of the beam.

Figure 4.8 shows the variation of Moment and End-slip with deflection. It is clear from the plot that the flexural capacity was limited by the strand slip. In other words, the resistance of the beam leveled off as the strand slip increased. Subsequent end slip measurements increased almost linearly with deflection, suggesting that the maximum bond strength was achieved at the point when the slip started. It was evident from this test that the embedment length provided was insufficient to anchor the strand that was cast in this beam.

Figure 4.9 displays a photograph of the beam taken when the deflection was at its maximum. The inclined flexural crack which can be clearly seen in this photograph was typical to tests which were associated with large end slip readings.

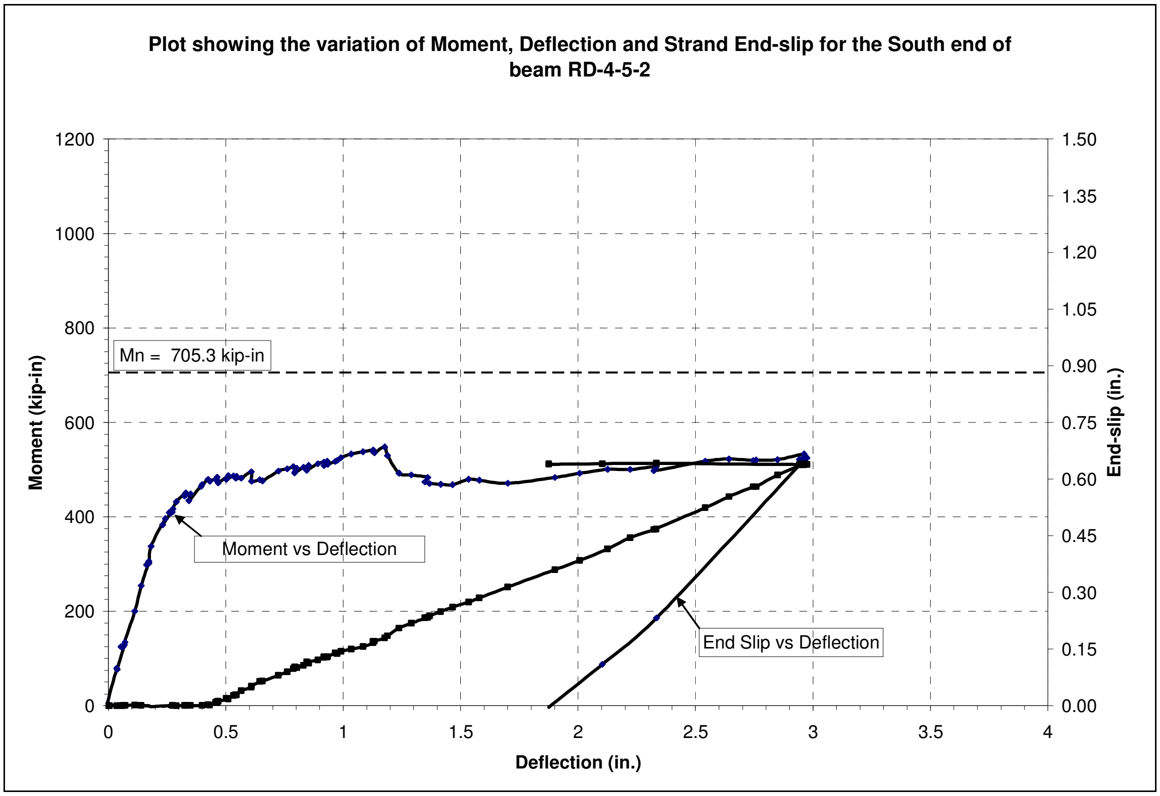

Figure 4.8: Moment-Deflection curve with end-slip for South end of beam RD-4-5-2

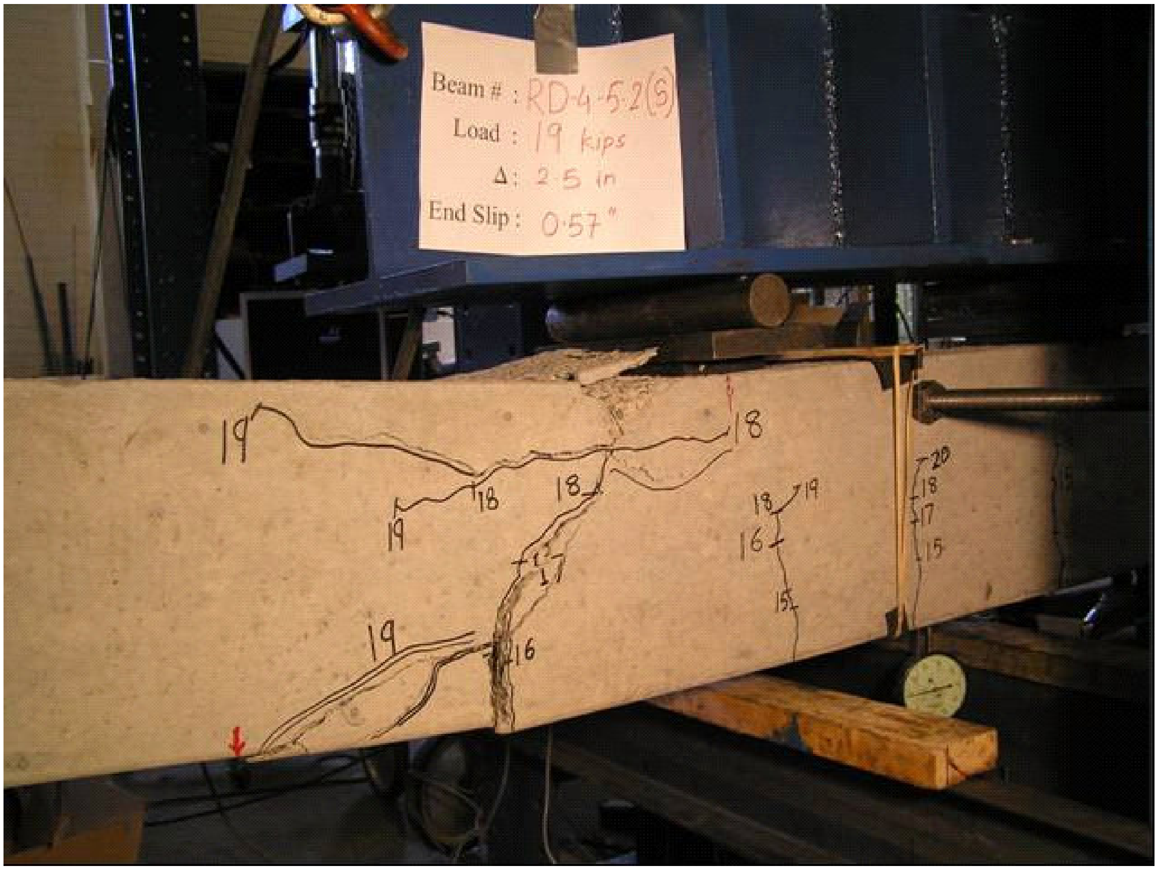

Figure 4.9: Photo showing the cracking pattern at the maximum deflection (Test: RD-4-5-2-S)

Typical example of Bond failure in I-shaped beams

Name of the Beam: ID-6-5-1

End of the beam tested: SOUTH

Test Date: 09/23/2005

Table 4.10: Test parameters for South end of the beam ID-6-5-1

TEST PARAMETERS	
Concrete Compressive Strength	**9840 psi**
Embedment Length(L_e)	**88 in.**
Span	**270 in.**
Failure Mode	**Bond**
Maximum Load	**60 kips**
Maximum Shear	**40 kips**
Maximum Moment	**3280 kip-in.**
Maximum Deflection attained	**3.5 in.**
Rebound after complete unloading	**2.0 in.**
Average NASP P.O value for strand "B"	**6.89 kips.**

Table 4.11: Transfer length data for the beam ID-6-5-1

	Transfer lengths (in.) for beam # ID-6-5-1		
		At Release	At the time of testing
South	Top	29.99	68.63
	Middle	11.04	26.67
	Bottom East	12.23	46.22
	Bottom Central	NA	NA
	Bottom West	2.56	9.1

Test Highlights

Initial flexural crack was noticed on the beam approximately at the mid-span of the beam at the load of 41.7 kips (Shear = 27.8 kips) and deflection of 0.58 in. Initial web shear cracks formed at the load of 48.6 kips (Shear = 32.4 kips) and at deflection of 0.85 in. The first strand slip of 0.01 in. was observed coincident with the first web shear cracks. A noticeable drop in load was also observed and the first strand slip of 0.01 in. was recorded. Interestingly, at a load of 48.6 kips, a small but sudden drop in load was observed. The web shear cracks were discovered only while mapping additional flexural cracks. Maximum load that the beam could sustain was 60.0 kips (Shear = 40 kips) when suddenly it dropped down to 56.6 kips. Further increments in deflection resulted only in increase of end slip while the load did not increase to it maximum value. Maximum moment sustained by the beam was 81% of its nominal capacity as calculated by strain compatibility. Deflection increments were stopped when total end slip was 0.75 in.

Failure of this beam was classified as bond failure since the end slip values were large and the maximum moment attained was lesser than its nominal capacity by approximately 20%. From the result of this test, it was clear that the embedment length of 88 in. was insufficient for the strand to develop enough anchorage required to achieve nominal capacity. Figure 4.10 shows the variation of Moment and End-slip with deflection. The plot shows the rate of increase of load reduces as the strand started slipping. The plot becomes horizontal as strand slip increases sharply. The increase of strand slip corresponds to large deflections during the later stages, and indicates that the demand of bond strength had increased beyond the maximum value the strand could offer. It can be seen from the plot that the end slip did not start with the first flexural cracks, but that strand slip can be associated with the formation of first web shear cracks. Figure 4.11 shows the variation of shear vs. average shear strain measured on the web of the beam. Figure 4.12 and Figure 4.13 present photographs taken just after first web shear cracking and at maximum deflection respectively.

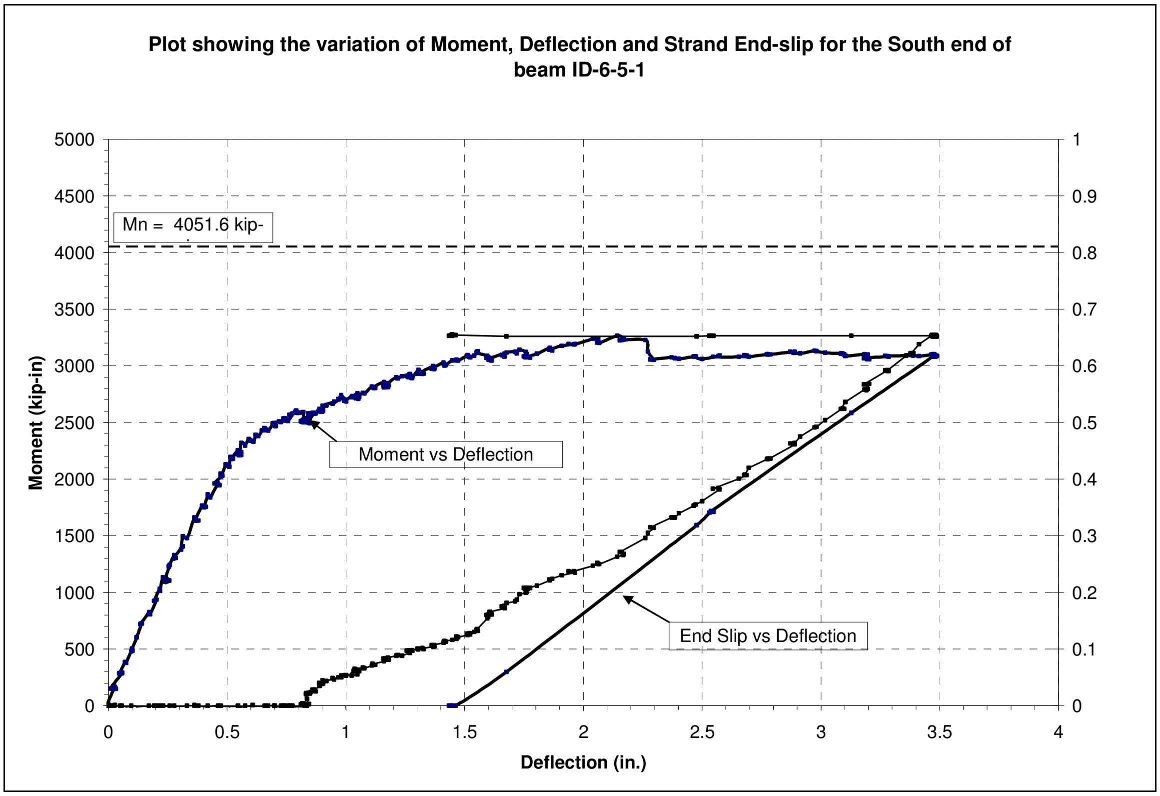

Figure 4.10: Moment-Deflection curve with end-slip for the South end of the beam ID-6-5-1

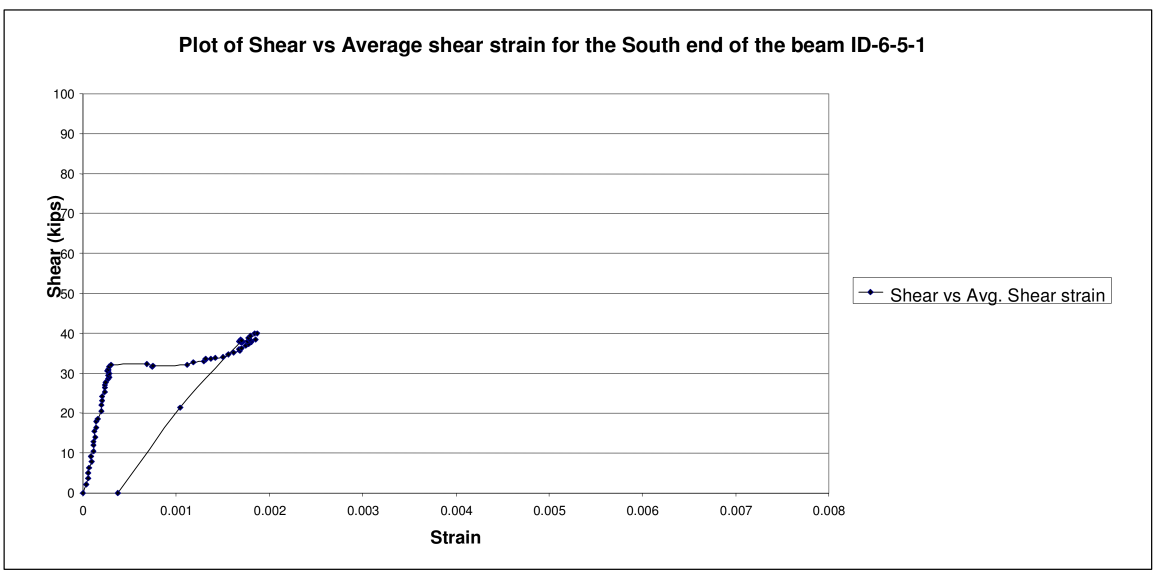

Figure 4.11: Plot of Shear vs. Average Shear Strain for the South end of the beam ID-6-5-1

Figure 4.12: Photo of the South end of the beam ID-6-5-1 showing the first web shear cracking

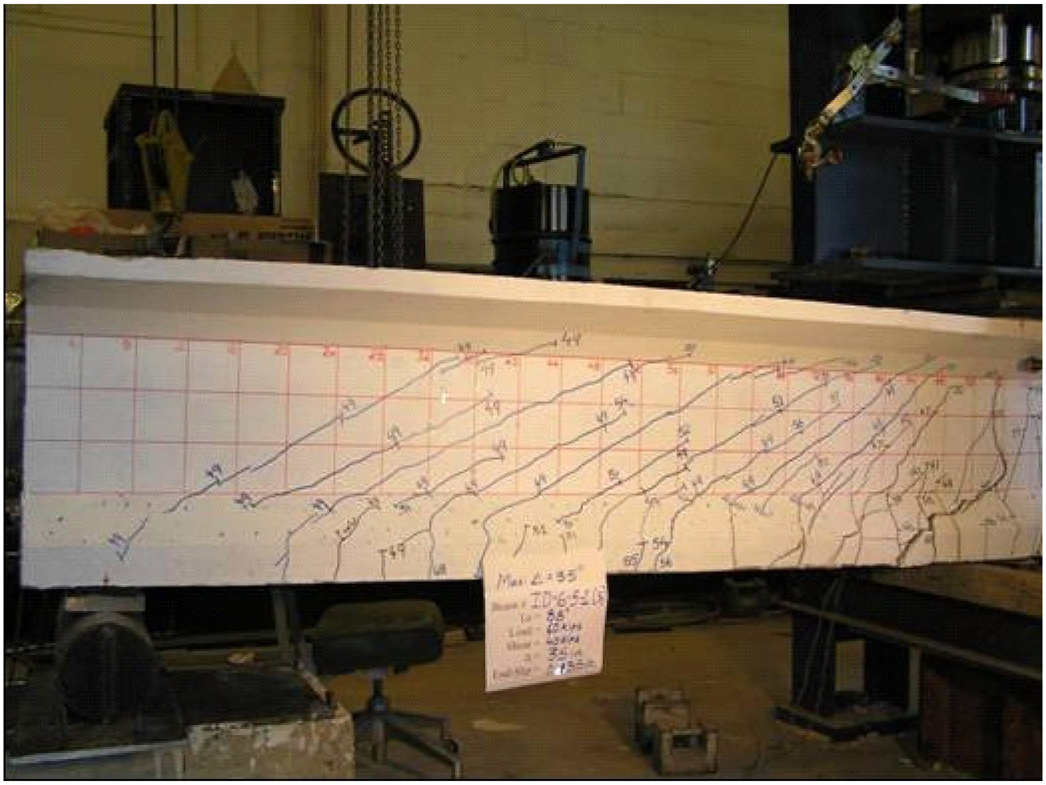

Figure 4.13: Photo of South end of beam ID-6-5-1 showing the cracking pattern at the maximum deflection

4.3.3 Shear Failure

Failure of this beam specimen was caused by a large single shear crack that occurred outside of the constant moment region. The shear failure occurred at a shear load lesser than its design capacity. However, it is noted that the I-beam was damaged at the precast/prestressed concrete yard when it fell from a flatbed truck. Visible cracking damage in the web denotes that the I-beam was twisted or racked when it fell. It is likely that the initial damage led to a reduced shear capacity.

The shear failure occurred before the beam reached its nominal flexural capacity. As noted above, web cracks pre-existed in the web. Loading caused shear cracks to propagate from the already formed cracks. At shear failure the two sides of the single large shear crack were completely separated with only the steel reinforcement holding it together. This type of failure occurred only once while testing one of the I-shaped beams.

In example of Shear Failure in I-shaped Beams

Name of the Beam: IA-6-6-2

End of the beam tested: NORTH

Test Date: 10/13/2005

Table 4.12: Test parameters for the North end of the beam IA-6-6-2

TEST PARAMETERS	
Concrete Compressive Strength	**8990 psi**
Embedment Length(L_e)	**88 in.**
Span	**270 in.**
Failure Mode	**Shear**
Maximum Load	**75.5 kips**
Maximum Shear	**50.3 kips**
Maximum Moment	**4125 kip-in**
Maximum Deflection attained	**3.2 in.**
Average NASP P.O value for strand "A"	**18.29 kips**

Table 4.13: Transfer length data for the beam IA-6-6-2

	Transfer lengths (in.) for beam # IA-6-6-2		
		At Release	At the time of testing
North	Top	20.22	NA
	Middle	-	-
	Bottom East	9.62	27.1
	Bottom Central	22.58	35.72
	Bottom West	15.48	29.95
South	Top	21.84	NA
	Middle	-	-
	Bottom East	14.18	28.62
	Bottom Central	14.92	24.49
	Bottom West	19.47	37.69

Test Highlights

Condition of the beam before starting the test can be seen from Figure 4.14. There were several initial cracks present on the beam with a significantly long crack at the junction of flange and web. These cracks were caused during the handling of the beam at the precast/prestressing plant.

The beam was loaded in two cycles on 13th and 14th October 2005 respectively. Permanent deflection after the first loading cycle was approximately 0.5 in.

The beam first cracked in flexure at the load of 44 kips (Shear = 29.3 kips) and a deflection of 0.5 in. First web shear cracks were also observed at the same load and deflection values. Two flexural cracks and three web shear cracks were noticed at this time. There was no noticeable end slip recorded with first web shear cracking. At the load of 58.5 kips (Shear = 39 kips) and deflection of 1.1 in., first end slip of 0.01 in. was noted. Along with deflection, load and end slip values increased gradually and at 75.3 kips (Shear = 50.2 kips) and at deflection of 2.9 in., shear cracks grew wider and spalling of concrete from the web of the beam was evident. At the next increment of deflection when deflection reached 3.1 in., the load suddenly dropped down to 73.8 kips. Subsequently, the beam failed in shear suddenly as the web concrete exploded from the beam. A diagonal crack had completely split the beam into two pieces with prestressing strands in the bottom bulb and distorted vertical stirrups left as the only connection between them.

Figure 4.15 shows the variation of Moment and End-slip with deflection. Figure 4.16 shows the variation of Shear stress with average shear strain. A photograph of the beam after shear failure is present in Figure 4.19

Figure 4.14: Photo showing the cracks present on the beam IA-6-6-2 before starting the test.

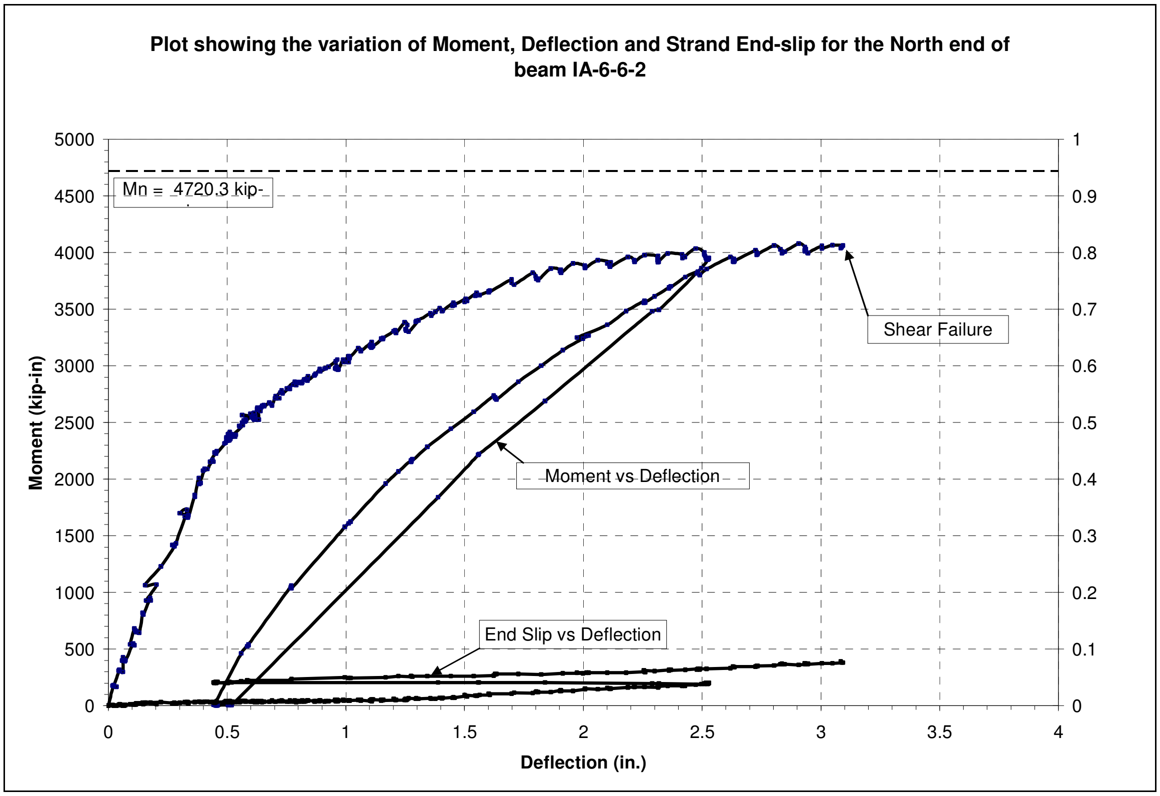

Figure 4.15: Moment-Deflection curve with end slips for the North end of the beam IA-6-6-2

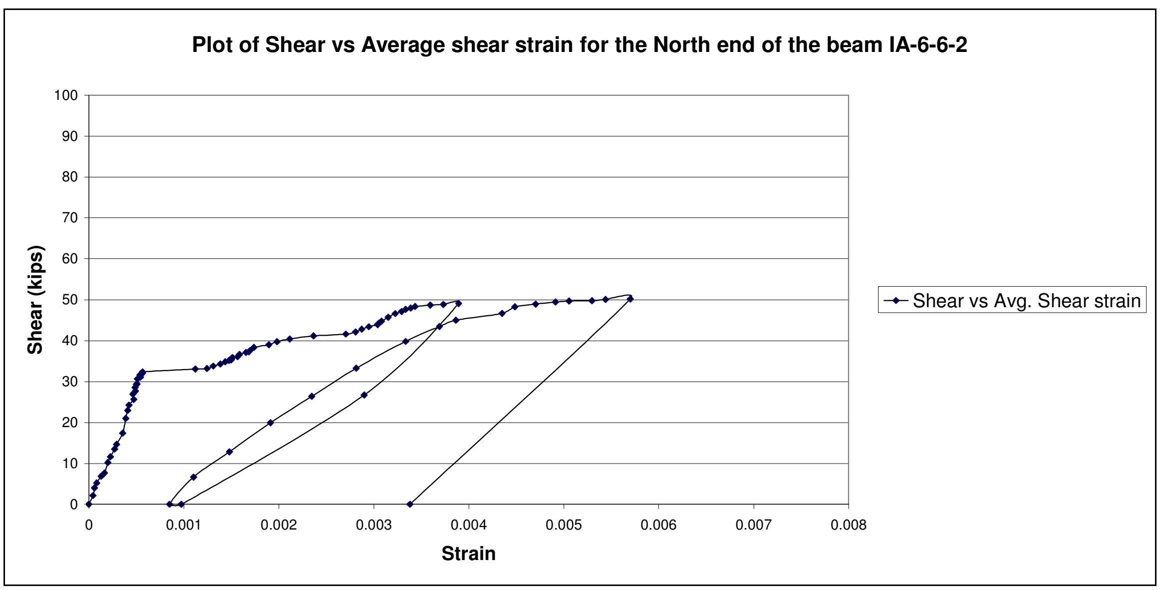

Figure 4.16: Plot of Shear vs. Average Shear Strain for the North end of the beam IA-6-6-2

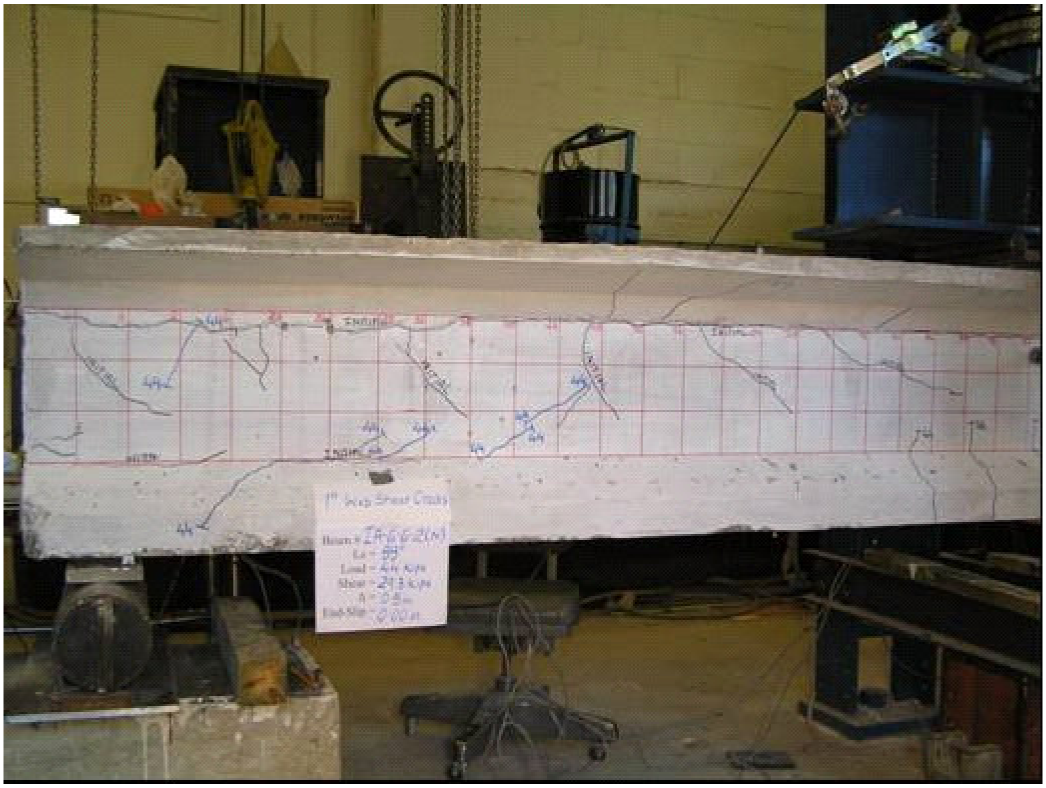

Figure 4.17: Photo of the North end of the beam IA-6-6-2 showing the first web shear cracking (incidentally the point of first flexural cracking as well)

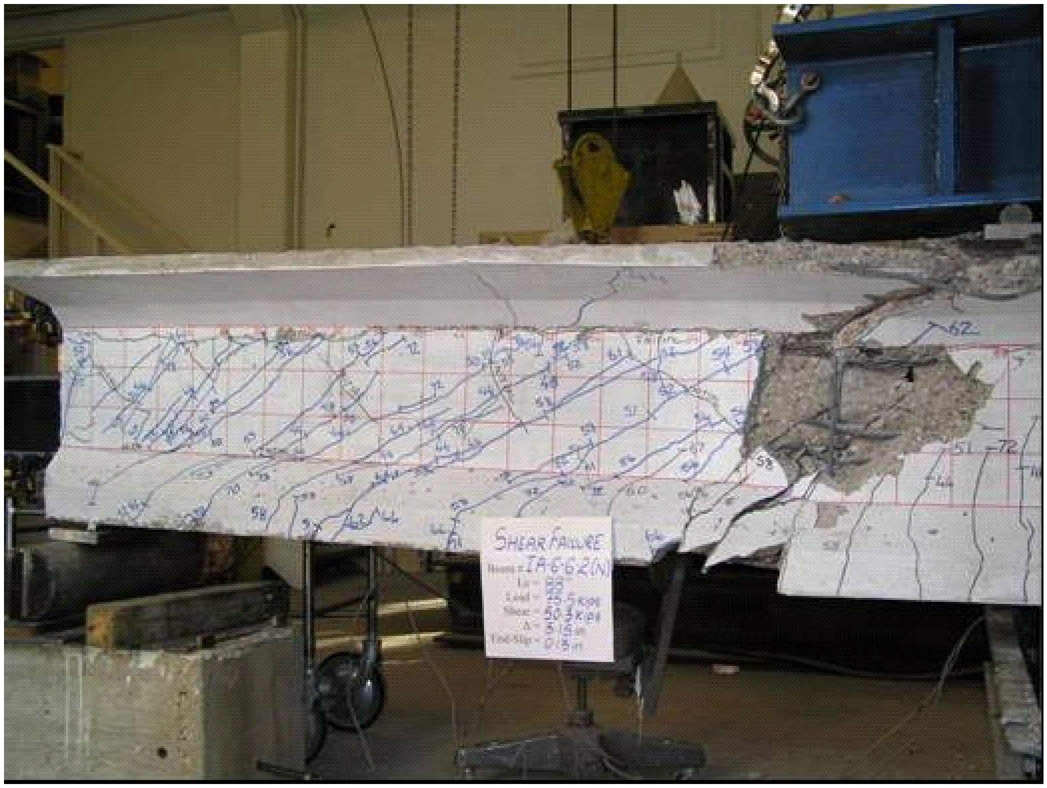

Figure 4.18: Photo of North end of beam IA-6-6-2 showing the cracking pattern at failure

4.3.4 Other Terminologies Used

Other than the results described above, end of test was mentioned as either (a) Failure did not occur or (b) Shear failure at opposite end.

(a) Failure did not occur:

Such a type of result was obtained when the beam did not fail in the above mentioned types of failures. The test was stopped due to either of following reasons –(i) The hydraulic actuator had run out of stroke during the test, (ii) Failure of beam could have resulted in damage that would have been detrimental for testing the second end of the beam.

(b) Shear failure at opposite end:

Mode of failure mentioned as "shear at opposite end" means that the beam specimen failed in shear at a location between the constant moment region and the end which was not being tested during that particular loading cycle. Absence of horizontal shear reinforcement in the above mentioned region coupled with the loading geometry which generated higher shear in the same region could have been the reason for such failures. Another possibility that could have been the cause of such failures was the presence of cracks formed during an earlier test performed on the opposite end of the beam.

CHAPTER V

5.0 DISCUSSION OF TEST RESULTS

5.1 INTRODUCTION

This chapter includes the analysis in three primary areas:

1) What influence does the concrete strength have on the development length for pretensioned prestressing strands?
2) What is the proper expression for development length?
3) What should be the minimum NASP Bond Test Value of the prestressing strand for achieving adequate anchorage?

The NASP Bond Tests in concrete clearly demonstrate that concrete strength can exert great influence over the bond of strand with concrete. This trend is also demonstrated in measured transfer lengths as the transfer length for a given strand was shortened as concrete strength increased. Likewise, the results from development length tests are analyzed to determine the influence of concrete strength. Based on the discussions, certain modifications to the current AASHTO equation for development length are recommended in this chapter. This chapter also includes comparisons between flexural test results to assess the validity of such recommendations.

5.2 EVALUATING DEVELOPMENT LENGTH FROM THE FLEXURAL TESTS

The development length is the length for which the strand must be fully embedded so that it gains enough anchorage to develop adequate tension stress so that the strand can support the nominal flexural capacity of the cross-section. The development length is distinguished from the embedment length as the embedment length is the length of bond that is actually provided. In the course of testing, a specific embedment length may be longer or shorter than the strand's development length. If a beam test results in a bond failure, then one must conclude that the embedment length provided was shorter than the required development length. Conversely, if a beam test results in a flexural failure, then one can conclude that the embedment length provided was longer than the required development length. Each independent beam test therefore becomes a single data point that tells us whether the embedment was sufficient or not. And largely, it is difficult to discern from a single test what the "true" development length must be.

Ideally, the "true" value of development would be when the flexural test results in simultaneous flexural, shear and bond failures. (Meyer 2002) Varying the embedment length between the values corresponding to complete flexural failure and complete bond failure will get us closer to identifying the "true" development length. Based on prior test results, the embedment length can be systematically lengthened or shortened for the purpose of bracketing the test results. In this manner, an accurate picture for development length may be obtained through multiple beam tests.

The variables for development length tests were embedment length, concrete strength and the type of strand. These parameters were changed for flexural tests on both rectangular and I-shaped beam specimens.

5.3. EFFECT OF CONCRETE STRENGTH ON BOND PERFORMANCE

Current ACI/AASHTO equation does not include the concrete strength parameter for calculating transfer and development length. However, results obtained during the flexural tests strongly suggest that the anchorage ability of the strands is improved as concrete strength increases. This section demonstrates the effects of increasing concrete strength on the results obtained during the flexural tests.

5.3.1 Direct Tabular method for demonstrating the effect of concrete strength on development length of prestressing strands

Table 5.1 summarizes the results from development length tests performed on Strand D cast in rectangular beams. In the Tables 5.1 through Table 5.3, ‘F’ denotes a flexural failure and ‘B’ denotes a bond failure. In Table 5.1 the results indicate that for embedment lengths of 73 in. and concrete release strengths of about 4 ksi (28 day strength of 7 ksi), Strand D was able to develop the necessary tension to contribute in achieving a flexural failure in the beam. However, at an embedment length of 58 in. tested at the opposite ends of the same beams, Strand D failed in bond. The tests would demonstrate that at 7 ksi concrete, the development length required for Stand D is less than 73 in. but greater than 58 in. The embedment length of 73 in. corresponds to 100% of the development length prescribed in the AASHTO while the embedment length of 58 in. corresponds to 80% of the code specified value.

Important to the purposes of this research, the bond of Strand D demonstrates marked improvement as concrete strengths increase. At a concrete strength of 11 ksi, Strand D was able to develop the necessary tension at embedment lengths of either 58 in. or 73 in. The test results indicate that for Strand D cast in 11 ksi concrete, the development length required is equal to or less than 58 in. Further, in Beam RD-10-5-1 and RD-10-5-2, Strand D was able to develop its tensile force in only 46 in. of bonded length. These tests indicate that for Strand D cast in 14 ksi concrete, the development length required is equal to or less than 46 in. The dark line in the table separates the zone of bond failures from the zone of flexural failures. The test results clearly show that the strand bond improves in development length applications with increase in concrete strength.

Table 5.1: Development Tests on rectangular beams with Strand D (0.5 in.)

Beam Tests on Rectangular Beams with Strand D (Average NASP Pull-Out value = 6870 lbs.)					
Beam No.	fc' RLS	fc' 56 days	Embedment Length (in.)		
	(psi)	(psi)	46	58	73
RD-4-5-1	4033	7050	-	B	F
RD-4-5-2	4033	7050	-	B	F
RD-6-5-1	6183	8500	-	F	F
RD-6-5-2	6183	8500	-	B	F
RD-6A-5-1	7960	11420	-	F	F
RD-6A-5-2	7960	11420	-	F	F
RD-8-5-1	8570	13490	-	F	F
RD-8-5-2	8570	13490	-	F,F*	-
RD-10-5-1	9711	14470	F	F	-
RD-10-5-2	9711	14470	F	F	-
F = Flexural failures					
B = Bond failures					
Note - * - Both ends were tested at an embedment length of 58 in. Both ends failed in flexure.					

Table 5.2 shows the results from development length tests performed on beams made with Strand A/B. The results show that: (1) Strand A/B bonded better with concrete than Strand D; and (2) the bond of Strand A/B improved as concrete strength increased. The

dark line in the table separates the zone of bond failures from the zone of flexural failures.

Table 5.2: Development length tests on rectangular beams with Strands A/B (0.5 in.)

Beam Tests on Rectangular Beams with Strand A/B (Average NASP A = 20210 lbs. and B = 20950 lbs.)					
Beam No.	**fc' RLS**	**fc' 56 days**	**Embedment Length (in.)**		
	(psi)	**(psi)**	**46**	**58**	**73**
RB-4-5-1	4033	7050	-	F	F
RB-4-5-2	4033	7050	-	F	F
RA-6-5-1	6183	8500	-	F	F
RA-6-5-2	6183	8500	F	F	-
RA-6A-5-1	7960	11420	-	F	F
RA-6A-5-2	7960	11420	F	F	-
RA-8-5-1	8570	13490	F	F	-
RA-10-5-1	9711	14470	F	F	-
F = Flexural failures					
B = Bond failures					

Table 5.3 summarizes the results of beam tests on rectangular beams made with 0.6 in. strands. The current AASHTO expression gives a development length requirement equal to 88 in. for 0.6 inch diameter strands. Test results show that flexural failures occurred at lengths of 88 in. and 73 in. for all concrete strengths. The results also show that bond failures occurred for the three concrete strengths when an embedment length of 58 in. was tested. However, when Strand A(0.6) was cast in concrete with release strength of 10 ksi and design strength of over 14 ksi, the strand was able to develop the required

tension force at an embedment length of 58 in. The dark line in the table separates the zone of bond failures from the zone of flexural failures. These results show clear improvements in strand bond behavior with increasing concrete strength.

Table 5.3: Development Tests on rectangular beams with Strand A (0.6 in.)

Beam Tests on Rectangular Beams with Strand A 0.6in (Average NASP value = 18290 lbs.)						
Beam End	fc' RLS	fc' 56 days	Embedment Length (in.)			
	(psi)	(psi)	58	70	73	88
RA-4-6-1	4033	7050	-	F	-	F
RA-4-6-2	4033	7050	B	-	F	-
RA-6-6-1	4855	8040	-	-	-	F
RA-6-6-2	4855	8040	B	-	F	-
RA-6-6-3	4855	8040	-	-	-	F
RA-8-6-1	5413	8220	-	-	-	F
RA-8-6-2	5413	8220	B	-	F	-
RA-10-6-1	9150	14610	-	-	-	F
RA-10-6-2	9150	14610	F	-	F	-
F = Flexural failures						
B = Bond failures						

The current ACI/AASHTO equation does not include the concrete strength parameter for calculating transfer and development length. However, results obtained during the flexural tests demonstrate that the anchorage ability of the strands is improved as concrete strength increases.

5.3.2 NASP Bond Test Values vs. Concrete Strengths and Transfer Length Recommendations

The standard NASP Bond Test is a test where a prestressing strand is pulled from concrete mortar. The mortar is made from sand, cement and water and possesses a one day compressive strength of 4500 to 5000 psi. The NASP Bond Test can be modified to perform the test in concrete with varying concrete strengths. However, the NASP Bond Test values used in the discussions regarding minimum Bond Values are pull-out strengths obtained from the standardized NASP Bond Test performed in mortar.

The results from NASP Pull-Out tests in concrete were compared by (Chandran 2006) and are presented in this section. Figure 5.1 presents the normalized NASP values obtained by dividing the NASP Pull-Out values in concrete by corresponding NASP values using standardized test (performed in mortar) versus the concrete strengths for the NASP tests in concrete. The tests demonstrate remarkable correlation between the bond-ability of prestressing strand and the concrete strength.

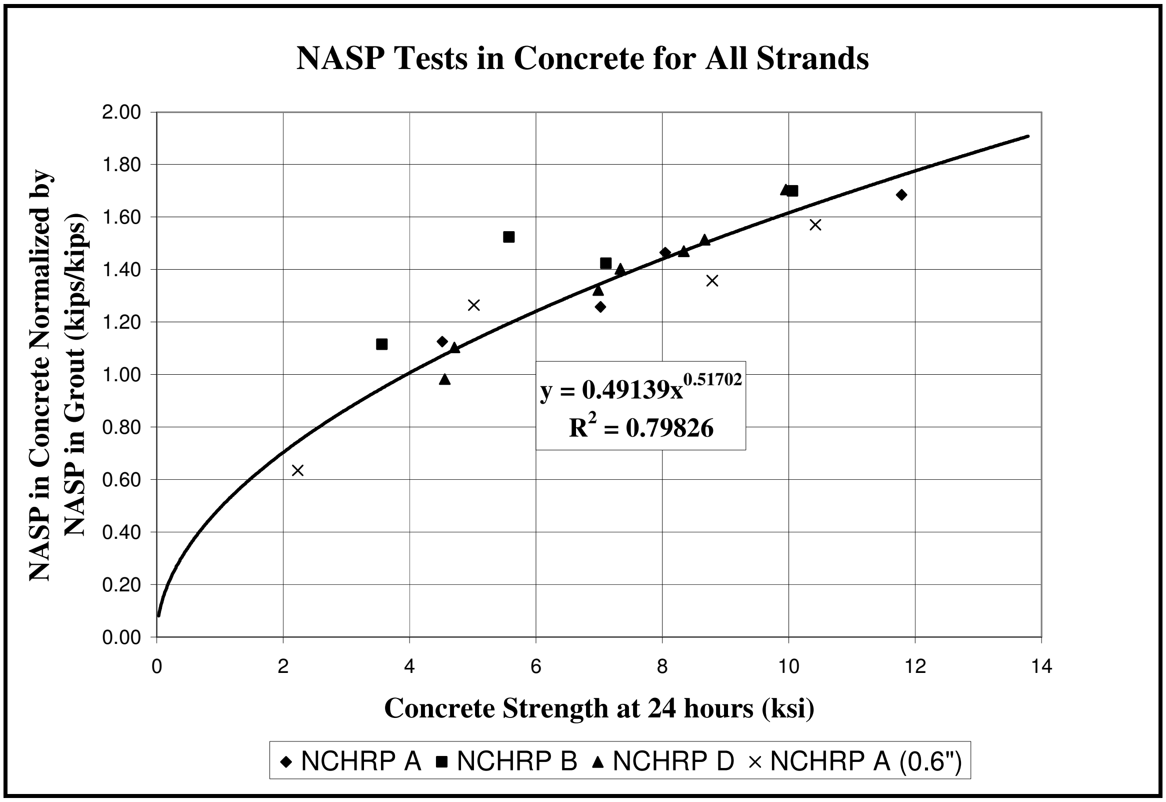

Figure 5.1 : Normalized NASP Pull-Out values versus concrete strengths. (Fig. No. 4.7, Chandran 2006)

Compared to a power regression, the above graph shows the following relationship between NASP values in concrete and NASP values in mortar (standard NASP values)

$$\frac{\left(NASP_{concrete}\right)}{NASP} = 0.49139\bar{f}_{ci}'^{\,0.51702} \quad \text{(Chandran 2006)}$$

The equation was further modified to fit the NASP values as a function of square root of concrete strengths. Figure 5.2 is a plot of normalized NASP values against the square roots of corresponding concrete strengths.

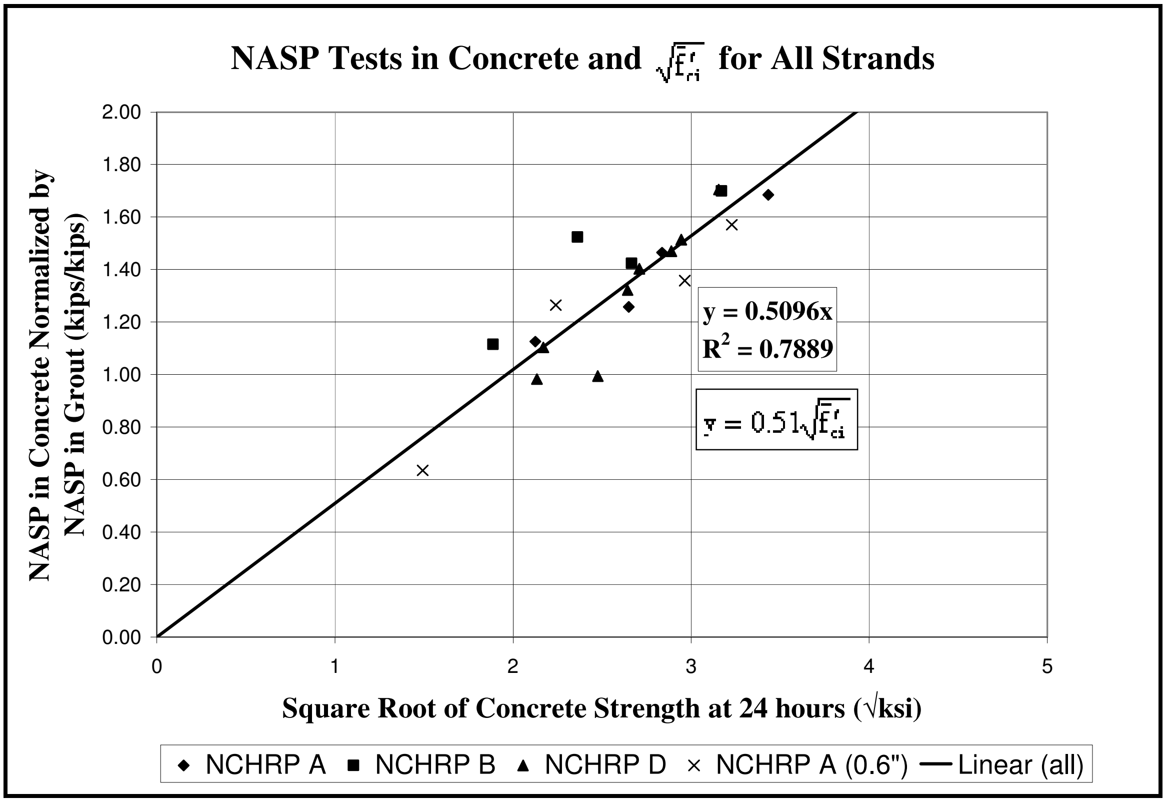

Figure 5.2: Normalized NASP Pull out values and $\sqrt{\bar{f}'_{ci}}$ (Fig. No. 4.8, Chandran[9])

Following relationship was obtained from the above graph.

$$\frac{(NASP_{concrete})}{NASP} = 0.51\sqrt{\bar{f}'_{ci}} \quad \text{(Chandran 2006)}$$

With the help of this relationship it was possible to use the Standardized NASP Bond Test, conducted in mortar, to estimate the bond strength as if the test was conducted in concrete with various strengths. Both of the graphs in Figures 5.1 and 5.2 demonstrate that the NASP Pull-Out value in concrete is directly proportional to the square root of concrete strength at one day of age. Furthermore, the results demonstrate that the average bond stress, taken as pull-out force divided by the bonded length, is directly proportional to the square root of the concrete release strength. From these results, Chandran (2006) suggested that since the transfer length is directly proportional to bond stress in the transfer zone, we can therefore conclude that transfer length is inversely proportional to the square root of concrete strength. He recommended a transfer length expression that is equivalent to the current design expression of 60 strand diameters for a release strength of 4 ksi, but shortens in proportion to the square root of the concrete strength at release:

$$l_t = \frac{120}{\sqrt{f_{ci}'}} d_b \geq 40 d_b \text{ (Chandran 2006)}$$

5.4 RECOMMENDED EQUATION FOR DEVELOPMENT LENGTH

The current ACI 318-02 and AASHTO code provisions do not include the effects of concrete strength when calculating the required development length of prestressing strands. As a result, the development length for strands are the same regardless of concrete strength; however the experimental results clearly demonstrate the required development length is lessened as concrete strength increases. Chandran (2006) established that transfer length is a function of concrete strength; higher concrete strength results in lower transfer lengths. The development length test results similarly demonstrate the necessity to include the effects of concrete strength into the development length equation.

5.4.1 Basis and Recommendation for the Transfer Length Equation

The approach develops from the findings of the research:

(i) The current AASHTO transfer length of $60d_b$ is adequate to predict the transfer length of prestressing strands in "normal strength concrete" (4 ksi release strength).

(ii) The data support modification to account for variations in concrete release strength, and to follow the finding that bond strength improves in proportion to the square root of the concrete strength.

(iii) The current AASHTO development length equation can be used to adequately predict required development lengths for "normal strength concrete," in the range of 4 ksi release strength and 6 ksi design strength.

(iv) The data demonstrate that shorter development lengths are required as concrete strength increases.

Based on Chandran's work (2006), discussed in section 5.3.2, the transfer length equation is modified by the square root of the concrete release strength, as follows.

$$l_t = \frac{120d_b}{\sqrt{f_{ci}'}}$$

where,

l_t = transfer length (in.),

f_{ci}'= release concrete strength (ksi), and;

d_b= diameter or prestressing strand (in.).

Using a concrete release strength of 4 ksi, this equation results in a transfer length equal to 60 d_b . The recommendation for transfer length is only modified so that a minimum length for transfer length is used, regardless of concrete strength. The recommendation effectively limits improvements in transfer length based on concrete release strength of 9 ksi which is less than the maximum release strength obtained in the beams cast for this research (9.7 ksi on rectangular beams). Therefore, the final recommended expression for transfer length is given by:

$$l_t = \frac{120}{\sqrt{f_{ci}'}} d_b \geq 40 d_b .$$

Equation 5-1: Recommended equation for transfer length of prestressing strands

5.4.2. Basis for and Recommendation for the Development Length Equation

Since the inception of the pretensioned, prestressed concrete industry in the USA, the development length equation was made from the addition of two components: (1) the transfer length, plus, (2) a "flexural bond length," which is the additional length of bond beyond the transfer length required for development. This traditional approach has been utilized in the industry for over the decades. The research continues to demonstrate that the approach is adequate to explain observed behavior and to adequately predict results. Thus, same approach is followed but with modifications to include the effects of varying concrete strengths:

(i) From the Tables 5.1 and Table 5.2 the results demonstrate that for all types of 0.5 in. strands, Strand A/B and Strand D, we had flexural failures at embedment lengths 73 in. The embedment length of 73 in. corresponds to

100% of the current code provision for development length for these specimens. The results included tests on beams made with concrete strength approximately 4 ksi at release and approximately 6 ksi at the time of the beam test.

(ii) The results uniformly indicate that the development length requirements diminish with increasing concrete strength.

(iii) The required development length calculated from the current code provisions is approximately 150 d_b, though some variations will exist due to variations in strand stressing, beam geometry and subsequent variations in computed prestress losses.. It is important to note that the factor $\kappa = 1.6$ is specifically excluded in the development of this formulation as the research shows the factor is not required as long as the NASP Bond Test Standard is met. Thus, the 73 in. corresponds to the specified development length according to both ACI 318-02 and AASHTO code provisions.

(iv) If the transfer length is approximately 60 db, and the development length is approximately 150 d_b, then the flexural bond length must be approximately 90 d_b.

The development length expression can then be written as,

$$l_d = l_t + \frac{225 d_b}{\sqrt{f_c'}}$$

where l_d= development length, l_t = transfer length, d_b= diameter of the prestressing strand, and f_c' = design concrete strength. Using a concrete design strength of 6 ksi, which roughly corresponds to a "normal concrete strength" within the industry plus forms the base case from the experimental results, the coefficient of 225 corresponds to flexural bond length of 90 strand diameters.

Like the transfer length expression, the development length expression is limited by a minimum value. The recommended expression for development length, therefore, is based on a limiting concrete strength of approximately 14 ksi, which is slightly less than the maximum concrete strength attained in beams tested in the research program (14.9 ksi). Thus, the recommended development length equation is as follows:

$$l_d = \left[\frac{120}{\sqrt{f_{ci}'}} + \frac{225}{\sqrt{f_c'}} \right] d_b \geq 100 d_b$$

Equation 5-2: Recommended equation for development length of prestressing strands

5.5 DISTRIBUTION OF FAILURE TYPES

This section presents the development length test results in graphical fashion. The result of each beam test, whether flexural failure or bond failure is plotted on a chart showing concrete strength vs. embedment length. The recommended design equation for development length is also shown on each of the charts. Note that the development length varies with concrete strength. For the purpose of plotting the values using the equation, release strength is taken as 66.7 percent of the design strength.

Figure 5.3 shows the results of development length tests on Strand D. Strand D demonstrated below average bond performance with a relatively low NASP Bond Test result (6890 lbs), longer transfer lengths and longer development length requirements than Strand A/B. Figure 5.3 shows that bond failures occurred in rectangular beams with embedment lengths of 58 in. at the lower concrete strengths. More importantly the figure shows improvement in strand bond behavior as concrete strengths improve. Note, however, that bond failures occurred in I-beams cast with Strand D. Results of the tests demonstrate that the Strand D, with an NASP Bond Test value of only 6890 lbs. may not provide adequate bond-ability with concrete.

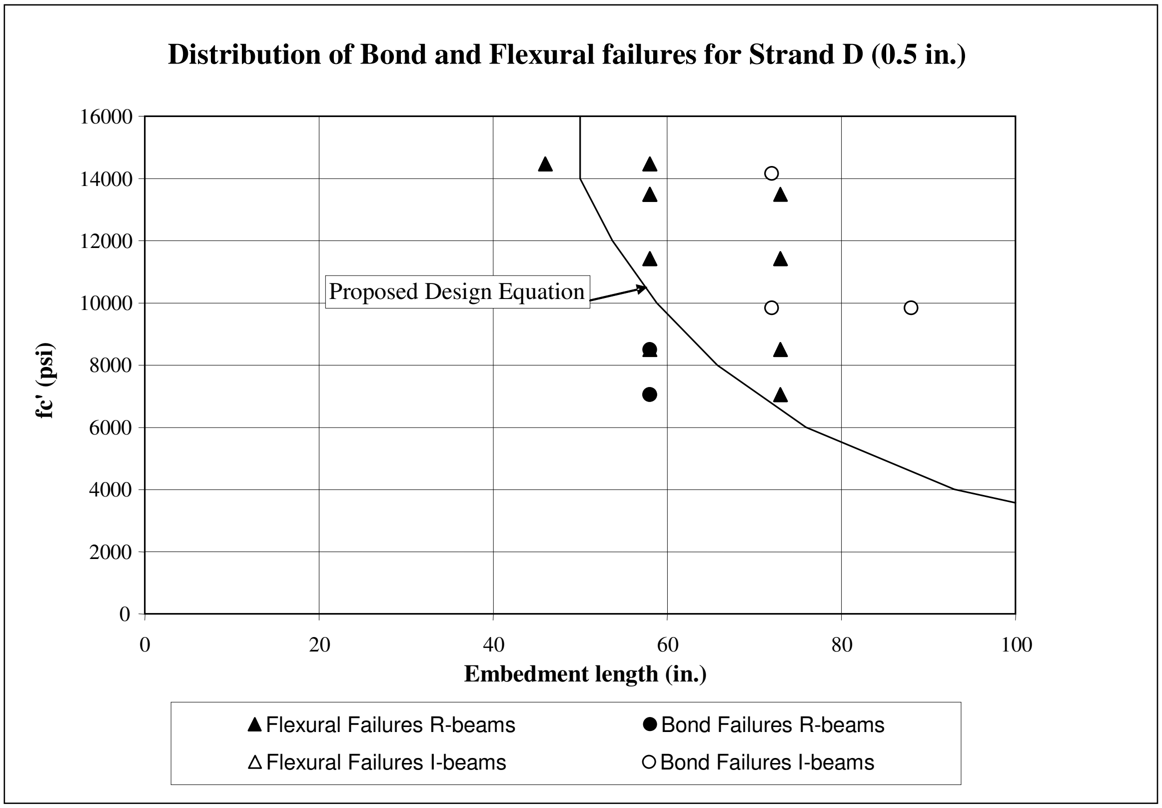

Figure 5.3: Distribution of Bond and Flexural failures for Strand D (0.5 in.)

Figure 5.4 shows the results of development length tests on Strands A and B. Note that the NASP Bond Test value was similar for both Strands A and B (about 21,000 lbs). Both of these strands can be considered "high bonding" since the NASP Bond Test value was so high. Strand B was cast in the 4 ksi rectangular beams and I-beams whereas Strand A was used in the higher strength rectangular beams. The chart shows that the high bonding strand was developed in all concrete strengths and for embedment lengths as short as 46 in. As in Fig. 5.3, the recommended development length equation is shown on the chart along with the beam test results.

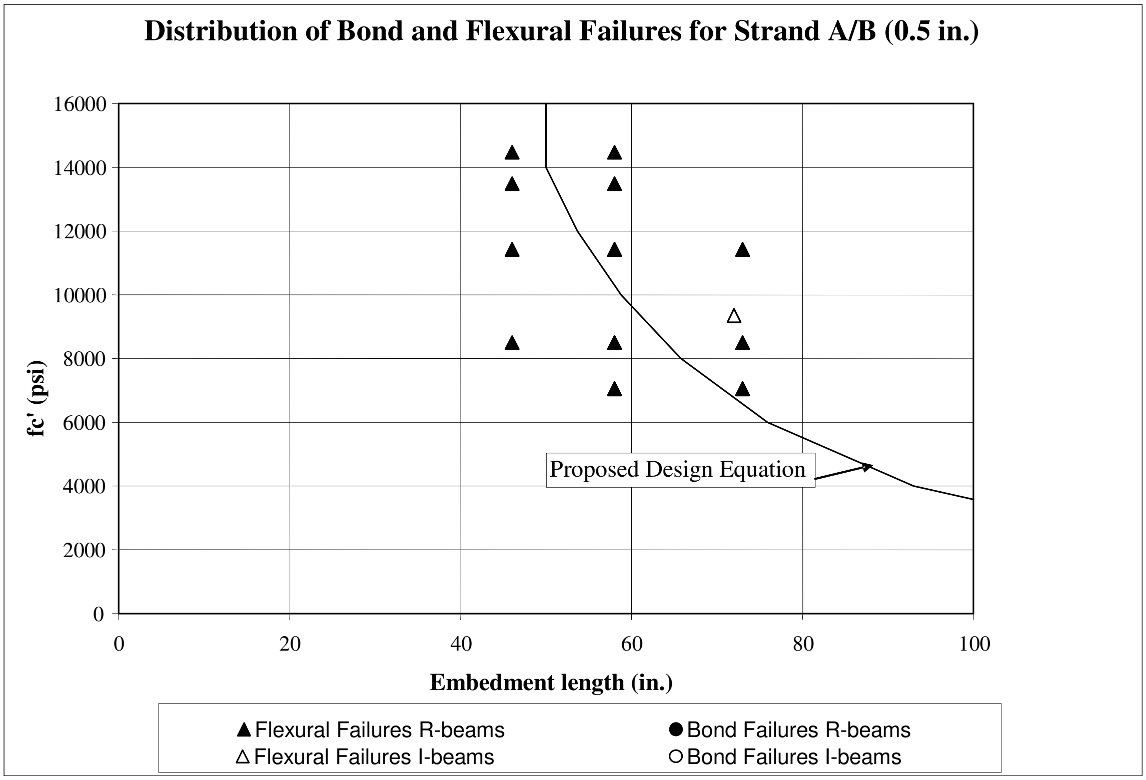

Figure 5.4: Distribution of Bond and Flexural failures for strand A/B (0.5 in.)

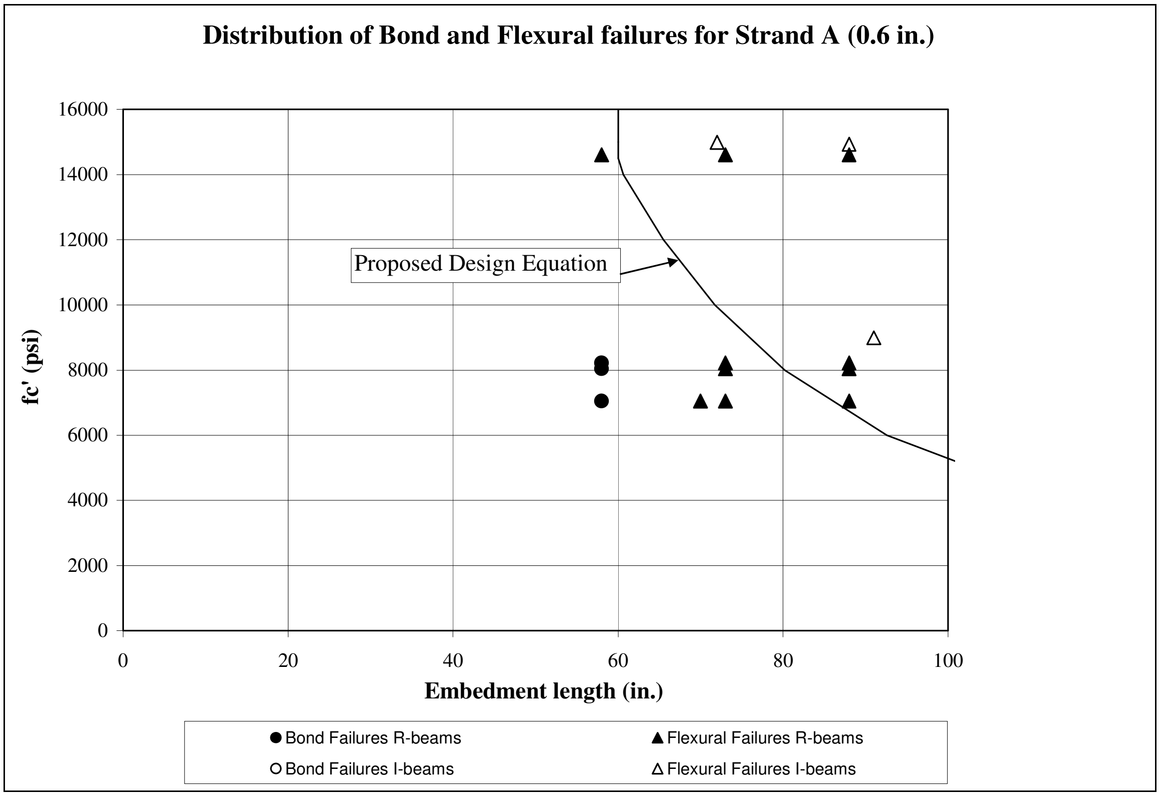

Figure 5.5: Distribution of Bond and Flexural failures for Strand A (0.6 in.)

Figure 5.5 shows the distribution of bond and flexural failures for strand A (0.6 in.) with respect to the concrete strength and the provided embedment lengths. We observe that there are no bond failures occurring in the region where provided embedment length exceeds the calculated development length using the proposed equation. The tests support the proposed equation for development length.

5.6 NASP VALUE AND BOND PERFORMANCE

Along with the recommendation for the development length design expression, it is equally important to recommend a minimum value from the NASP Bond Test. First of all, however, it was important to establish a correlation between the NASP Pull-Out test values and the bond performance of the same strands in transfer and in development length tests. Chandran (2006) demonstrated that the NASP Bond test had good correlation with measured transfer lengths. Brown (2004) measured transfer lengths and performed flexural tests on rectangular shaped beams. Table 5.4 and Table 5.5 summarize the test results and the failure modes from obtained from flexural tests performed by Brown. The NASP Pull-Out Test Values are also given.

Table 5.4: Failure Modes on Single Strand Beams (Brown 2003)

Beam Tests on Rectangular Beams by Matthew Brown (2003) - Single Strand Beams				
Beam No.	fc' 56 days	Average NASP P.O Value	Embedment Lengths (in.)	
	(psi)	(lbs.)	58	73
II11	6290	4140	B	F
II12	6280	4140	B	B
FF11	6260	7300	V	F
FF12	6070	7300	B	F
HH11	6330	10700	F	F
HH12	6300	10700	B	F
AA11	6220	14950	F	F
AA12	6160	14950	F	F
F = Flexural Failure				
V = Shear Failure				
B = Bond Failure				

Table 5.5: Failure Modes on Beams made with Two Strands (Brown 2003)

Beam Tests on Rectangular Beams by Matthew Brown (2003) - Double Strand Beams				
Beam No.	fc' 56 days	Average NASP P.O Value	Embedment Lengths (in.)	
	(psi)	(lbs.)	58	73
II21	6290	4140	B	F
II22	6280	4140	B	B
FF21	6260	7300	F	F
FF22	6070	7300	F	F
HH21	6330	10700	F	F
HH22	6300	10700	F	F
AA21	6220	14950	F	F
AA22	6160	14950	F	F
F = Flexural Failure				
V = Shear Failure				
B = Bond Failure				

Strand II had the lowest NASP Bond Test value, only 4140 lbs. One can see also that Strand II performed the worst of the four strands in both single strand and double strand beams, with bond failures at the AASHTO development length of 73 in.

Strand FF from Brown's research is the same strand labeled Strand D in the NCHRP research. From Tables 5.4 and 5.5 Brown reported a NASP Bond Test value of 7300 lbs for Strand FF. This compares to a NASP Bond Test value of 6890 lbs. in the NCHRP testing. Strand FF demonstrated ability to develop adequate tension in an embedment length of 73 in. in the rectangular beams. However, if one looks at the results in I-shaped beams, one can see that Strand D, or Strand FF was unable to develop adequate strand tension in 73 in.

Also from Brown's NASP Round IV testing, Strand HH demonstrated ability to develop adequate strand tension in 73 in. The NASP Bond Test value was 10,700 lbs. One bond failure occurred at an embedment lengths of 58 in. This occurred in a single strand beam. The results from NASP Round IV testing reported by Brown indicate that the bond performance of Strand HH was adequate.

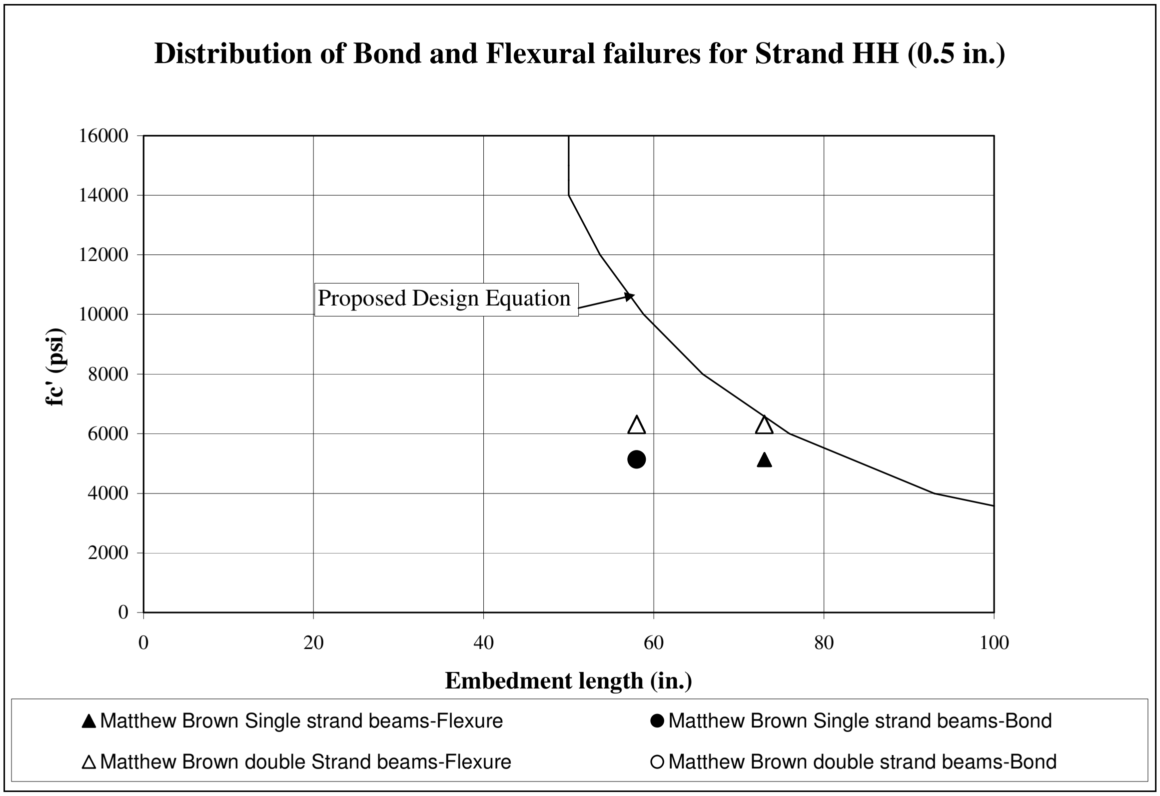

Figure 5.6: Distribution of bond and flexural failures for strand HH (Brown 2002)

Figure 5.6 shows the distribution of bond and flexural failures for strand HH (0.5 in.) with respect to the concrete strength and the provided embedment lengths. We observe that there are no bond failures occurring in the region where provided embedment length exceeds the calculated development length using the proposed equation. The tests support the proposed equation for development length and also indicate that bond performance of strand HH was adequate.

No Bond Failure was recorded on the beams with Strand AA. Comparing the NASP values of these strands following observation can be made; as the NASP value increases, chances of bond failure at provided embedment length decreases. In other words, Strand

II had the lowest NASP value and highest number of Bond Failures, Strand FF and Strand HH had NASP values lying between those of Strand II and Strand AA and bond failures were noted on lesser occasions than for Strand II. Strand AA had highest NASP value and no bond failures, suggesting that it was capable of developing enough anchorage so as to achieve flexural failures. It becomes clear that a higher NASP value indicate better bonding qualities for the strand.

Table 5.6 presents the number of failures obtained for all types of strands (0.5 in.) including Matthew Brown's strands. In the table, strands are arranged in the order of their increasing NASP Pull-Out values. Number of bond failures obtained at 58 in. and 73 in. embedment lengths are shown in the table.

Table 5.6: Comparison of number of bond failures at 58 in. and 73 in. of embedment lengths for all 0.5 in. strands including rectangular and I-shaped beams and including the strands tested by (Brown 2002)

Strand name	NASP Value (lbs.)	Number of bond failures	
		58#	**73#**
II	4140	4	2
D	6590	3	2*
FF	7300	1	-
HH	**10700**	**1**	**-**
AA	14950	-	-
B	20210	-	-
A	20950	-	-
# - embedment lengths in inches			
* - embedment lengths were 72 in. instead of 73 in.			

It can be observed that number of bond failures go on reducing for strands with increasing NASP Pull-Out values. Strand HH with NASP Pull-Out value of 10700 lbs. lies at a critical position such that strands having lower NASP Pull-Out values sustained bond failures while none of the strands having higher NASP Pull-Out value than that of strand HH suffered any bond failures. 58 in. and 73 in. of embedment length corresponds to 80% and 100% of code provision for development length. Strand HH suffered a bond failure for 58 in. but none for 73 in. This explains that 10,700 lbs. is adequate to develop enough anchorage for achieving flexural failures at code specified development length.

CHAPTER VI

6.0 SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

The research program involved development length tests on two types of beam specimens. Four types of strands were employed to cast 43 rectangular shaped beams and eight I-shaped beams. Both 0.5 in. and 0.6 in. diameter strands were included in the testing program. The beam specimens had concrete release strengths varying between 4 ksi and 10 ksi for both types of beams. Transfer lengths were measured on all beam specimens using the end slip of the strands with the help of clamps attached to the strands. Transfer lengths were also measured using the concrete surface strain measurements. As many as 50 flexural tests were carried out on the rectangular beams and 14 flexural tests on I-shaped beams. Values of load, deflection, end slips were recorded electronically as well as manually along with photographic records of failure stages and crack patterns. For I-shaped beam specimen concrete surface strains were measured at 36 in. from the end of the beam and vertically at the center of the web.

Prestressing strand anchorage requirements were assessed using the data collected from the development length tests. Results from the development length tests were compared to the NASP Pull-Out values of corresponding strands.

Based on the failure modes during the development length tests, effect of concrete strength on the bond performance was analyzed. The current ACI/AASHTO code requirements for development length of prestressing strands are assessed for their effectiveness in predicting accurate anchorage requirements.

6.1 CONCLUSIONS

1. Development length tests can be used to asses the bond performance of prestressing strands.
2. The ability of a prestressing strand to bond with concrete is affected by concrete strength. Increasing concrete strength improves the bond*ability* of a given prestressing strand.
3. The development length requirement for a particular strand is reduced if cast in higher strength concrete.
4. The NASP Bond Test provides a good indicator of strand bond performance in a pretensioned concrete beam.
5. The required development length shows a clear relationship with the NASP Bond Test values of the prestressing strand. Higher NASP Bond Test values result in shorter development lengths.
6. Rectangular beams with all types of strands were able to achieve flexural failures at embedment length equals to or less than the ACI/AASHTO specified development length.
7. With increased concrete strength it is possible to achieve flexural failures at an embedment lengths less than the ACI/AASHTO specified value.

8. Current ACI/AASHTO code provisions may overestimate the required development length of prestressing strands in higher strength concretes.
9. I-shaped beams were more susceptible for bond failures than the rectangular beams owing to the higher incidence of web shear cracks being developed in I-shaped beams rather than rectangular beams.

6.2 RECOMMENDATIONS

1. ACI 318-02 and AAHSTO code equations for development length should include a parameter reflecting the reduced transfer length with increasing concrete release strength. Further, the flexural bond length is reduced by higher strength concrete as well. The recommended equation for development length is:

$$l_d = \left[\frac{120}{\sqrt{f_{ci}'}} + \frac{225}{\sqrt{f_c'}} \right] d_b \geq 100 d_b$$

Where l_d= development length (in.), f_{ci}' = release concrete strength in ksi, f_c'= design concrete strength in ksi and, d_b= diameter of prestressing strands in inches.

2. A relatively large database has been collected during the course of this research project. That data include crack patterns, crack spacing and surface strain measurements on I-shaped beams. A more detailed analysis should be made using the information embedded in the summary reports for better understanding of the failure mechanisms.

3. More data should be collected to compare NASP Pull-Out values with transfer and development lengths of prestressing strands. A further mathematical analysis should be carried out to conclusively relate the NASP Pull-Out value with the transfer and development lengths of prestressing strands.
4. An average NASP Pull-Out value over six tests of 10,000 lbs. is recommended to ensure adequate anchorage at embedment lengths equal to or higher than ACI/AASHTO Code development length provision.
5. NASP Pull-Out test showed a very good correlation to the flexural test results. For further research on transfer and development length tests, NASP Pull-Out test should be accepted as a standard for predicting the bond characteristics of prestressing strands.
6. Unknown factors affecting the bond quality of prestressing strands should be investigated. Surface condition of prestressing strands should be included as a factor while assessing the bond characteristics of prestressing strands in addition to the NASP Pull-Out value and strength of concrete in which the strand is embedded.
7. Effect of admixtures on the transfer and development length tests should be studied with more development length tests carried out while changing the proportions of different admixtures in the concrete.

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APPENDIX A

DEVELOPMENT LENGTH TEST SUMMARIES FOR RECTANGULAR BEAMS WITH STRAND D (0.5 IN.)

BEAM NAME: RD-4-5-1
END: NORTH
DATE: 07/21/2005

TEST PARAMETERS	
Concrete Compressive Strength	**7050 psi**
Embedment Length(L_e)	**73 in.**
Span	**162 in.**
Failure Mode	**Flexure**
Maximum Load	**23.3 kips**
Maximum Moment	**804 kip-in**
Deflection @ Failure	**3.3 in.**
Rebound after complete unloading	**2.3 in.**
Average Transfer Length (L_t) @ release	**32.8 in.**
@ time of testing	**38.6 in.**
Average NASP P.O value for strand "D"	**6.89 kips**

TEST SUMMARY

Load was applied in approximately 2.5 kips increments till first flexural cracking. Beyond this point the deflection was incremented by 0.03 in. till total deflection reached 1.00 in. Further increments of deflection were kept 0.05 in. till deflection of 2.0 in. Increments were set to 0.1 in. from this point up to failure.

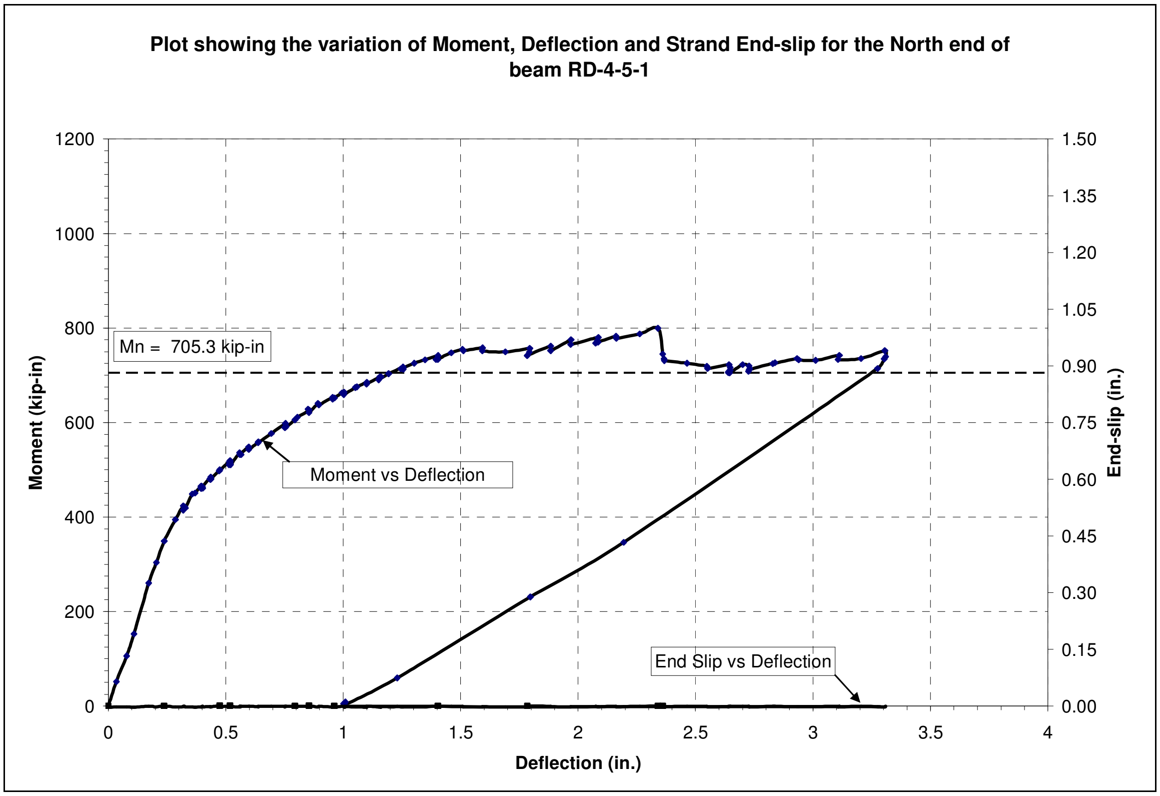
First flexural cracking occurred at a load of 12.3 kips (deflection 0.3 in.). The first flexural cracks formed at three spots, one of which was exactly under the point load whereas the other two were approximately equal distance from the central crack. With gradual loading these cracks propagated upward and diagonally towards the top rollers which were acting as two point loads.

No significant changes took place till the load reached a value of 22.3 kips (1.6 in. deflection). At this load cracks were clearly heard as the load was incremented. At load of 22.4 kips (2.3 in. deflection), cracks were heard for a longer time, hence sufficient time was allowed to pass before the next increment.

Cracks formed were being widened only on the South side of the beam. At this point it was noticed that one of the bottom rollers had rolled up to its limit and further horizontal displacement was stopped from both ends.

Concrete crushing failure was observed at a load of 21.5 kips. (deflection = 3.4 in.). Though the End-slip at the testing end (North) remained at 0.00 in, End-slip of 0.02 in. was observed at the South end.

Cracking pattern included 9 cracks in the middle 60 in. span with average crack spacing of 7.5 in. No inclined flexural crack was noticed.



Cracking pattern for Beam RD-4-5-1 being loaded at North end.

BEAM NAME: RD-4-5-1
END: SOUTH
DATE: 07/21/2005

TEST PARAMETERS	
Concrete Compressive Strength	**7050 psi**
Embedment Length(L_e)	**58 in.**
Span	**132 in.**
Failure Mode	**Flexure/Bond Failure**
Maximum Load	**28.1 kips**
Maximum Moment	**759 kip-in**
Deflection @ Failure	**1.6 in.**
Rebound after complete unloading	**1.0 in.**
Average Transfer Length (L_t) @ release	**31.0 in.**
@ time of testing	**42.3 in.**
Average NASP P.O value for strand "D"	**6.89 kips**

TEST SUMMARY

Load was applied in approximately 2.5 kips increments till first flexural cracking. Beyond this point the deflection was incremented by 0.03 in. till total deflection reached 1.00 in. Further increments of deflection were kept 0.05 in. till failure.

First flexural cracking occurred at a load of 17.0 kips while deflection at this point was noted as 0.2 in. The first flexural cracks formed at three spots, one of which was exactly under the point load whereas the other two were approximately equal distance from the central crack. With gradual loading these cracks propagated upward and diagonally towards the top rollers which were acting as two point loads.

Strand end-slip was first noted at the load of 20.5 kips (deflection 0.5 in.) then on end-slip continued as load was gradually increased. Also at the same load, a single large crack was observed approximately midway between the South end support and the first load point from that end.

The maximum deflection attained was 1.6 in. and maximum load value noted was 28.1 kips. At this point the load dropped suddenly to 25.1 kips. Though the maximum moment attained was 106% of the calculated value of nominal capacity, crushing of top surface of concrete was not observed.

This crack and the end-slip readings demonstrated the Bond Failure. Loading was immediately stopped as South end was the first end of this beam to be tested. Beam was unloaded and the deflection at zero load was found to be 0.6 in. However, End-slip was not recovered at all. The other end did not have any end-slip.

Crack pattern shows 7 flexural cracks in the middle 40 in. span with average crack spacing of 6.7 in. An inclined flexural crack was observed rising from Stn. 29 and Stn 32 and joining at approx. 3 in. from bottom to form a single crack.

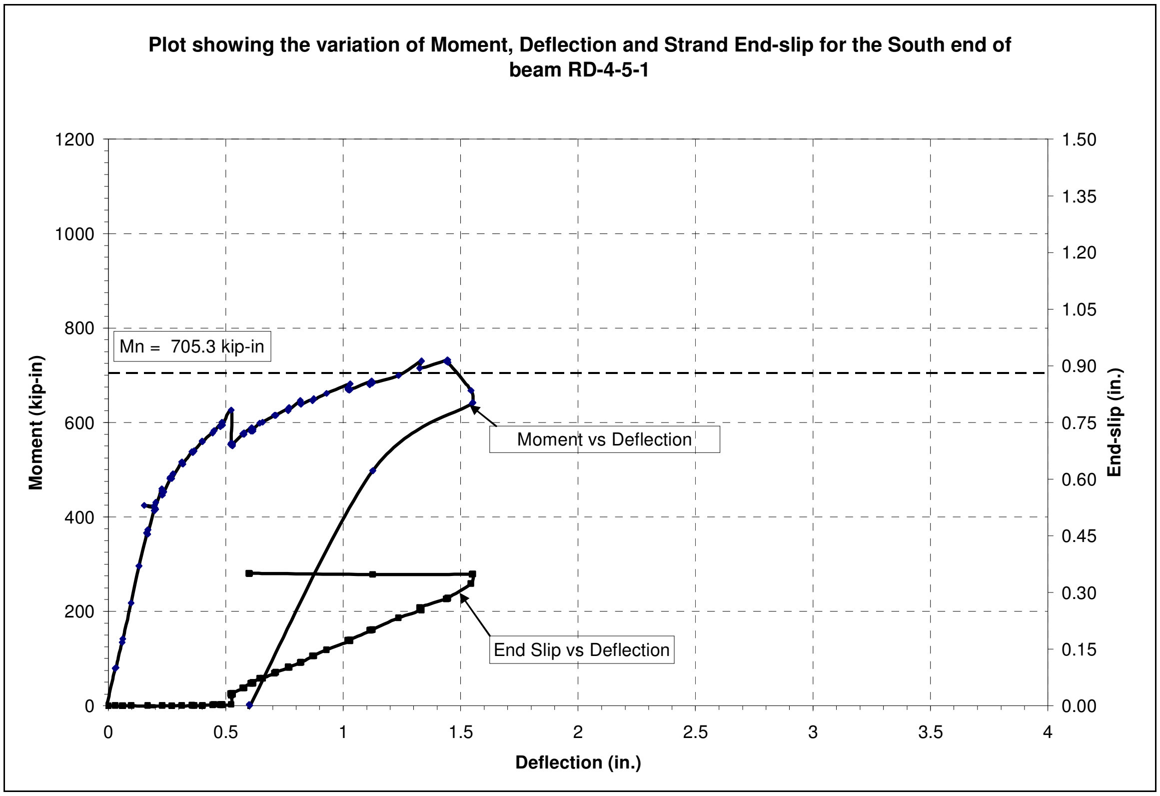


Photo Showing cracking pattern for Beam RD-4-5-1 being loaded at South end.

BEAM NAME: RD-4-5-2
END: NORTH
DATE: 07/25/2005

TEST PARAMETERS	
Concrete Compressive Strength	**7050 psi**
Embedment Length(L_e)	**73 in.**
Span	**162 in.**
Failure Mode	**Flexure**
Maximum Load	**24.1 kips**
Maximum Moment	**831 kip-in**
Deflection @ Failure	**2.7 in.**
Rebound after complete unloading	**1.7 in.**
Average Transfer Length (L_t) @ release	**32.8 in.**
@ time of testing	**63.1 in.**
Average NASP P.O value for strand "D"	**6.89 kips**

TEST SUMMARY

Load was applied in approximately 2 kips increments till first flexural cracking. Beyond this point the deflection was incremented by 0.03 in. till total deflection reached 1.00 in. Further increments of deflection were kept 0.05 in. up to 2.0 in. From this point till failure deflection increments were set to 0.1 in.

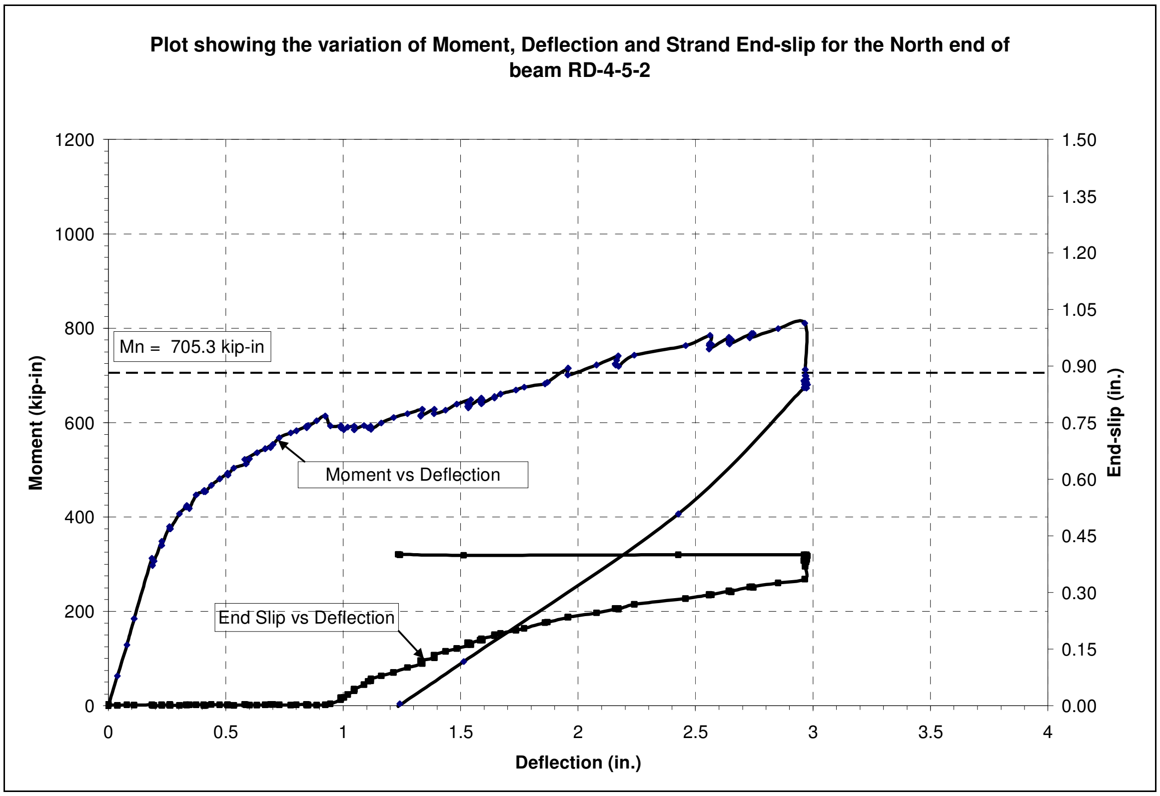
First flexural crack was observed at 11.2 kips at deflection of 0.3 in. Initially three cracks were noted at two point loads and at approximately midpoint of the two load points.

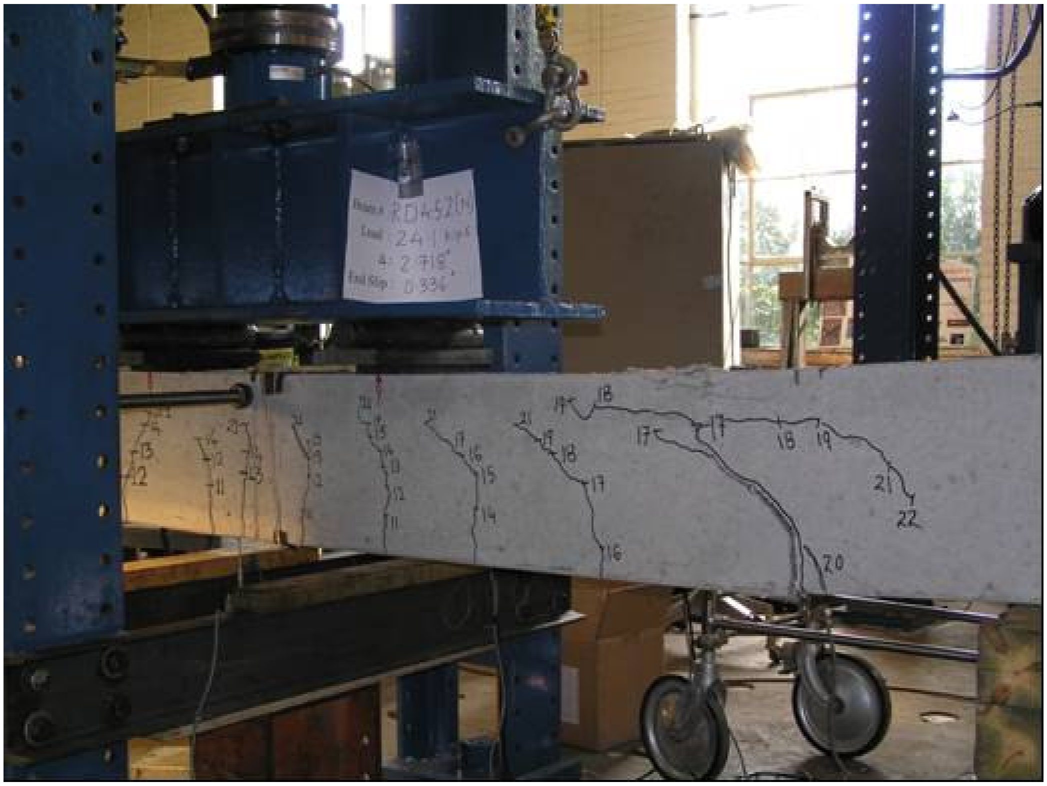
Another pair of flexural cracks was seen at 16.3 kips (deflection = 0.7 in.). At the load of 17.2 kips (deflection = 0.9 in) an inclined flexural crack was suddenly discovered at Stn. 41. At the same load and same deflection, first end-slip was noted as 0.02 in.

As the load reached 17.3 kips (deflection 1.0 in.), it was observed that the end-slip continued to increase without any further increments of load. Loading was halted for two minutes for allowing the end-slip to attain a constant value.

Loading was continued further and at 18.1 kips (deflection 1.2 in.) the inclined flexural crack appeared to grow in width drastically. Crack width continued to grow gradually from there on and as the load reached 24.1 kips (deflection 0.7 in.) end-slip of 0.0015 in. was noted on the South end. At the same load and deflection concrete crushing was observed at the top surface. After approximately 5 seconds another concrete crushing was noted with sudden spalling of concrete at the location where the inclined flexural crack reached its topmost position.

Cracking pattern included 9 flexural cracks in middle 59 in. span with average crack spacing of 7.4 in. An inclined flexural crack was noticed rising from Stn. 42 which later bifurcated (approx. 3 in. from the bottom) to Stn. 33.





Cracking pattern for Beam RD-4-5-1 being loaded at North end.

BEAM NAME: RD-4-5-2
END: SOUTH
DATE: 07/25/2005

TEST PARAMETERS	
Concrete Compressive Strength	**7050 psi**
Embedment Length(L_e)	**58 in.**
Span	**132 in.**
Failure Mode	**Bond Failure**
Maximum Load	**19 kips**
Maximum Moment	**513 kip-in**
Deflection @ Failure	**2.5 in.**
Rebound after complete unloading	**1.7 in.**
Average Transfer Length (L_t) @ release	**49.7 in.**
@ time of testing	**51.8 in.**
Average NASP P.O value for strand "D"	**6.89 kips**

TEST SUMMARY

Load was applied in approximately 2 kips increments till first flexural cracking. Beyond this point the deflection was incremented by 0.03 in. till total deflection reached 1.00 in. Further increments of deflection were kept 0.05 in. up to 2.0 in. From this point till failure deflection increments were set to 0.1 in.

First flexural crack was observed at 11.4 kips at deflection of 0.2 in. Initially only single crack was observed at midway between the two point loads. Two more cracks were noted at two point loads at 15.4 kips (deflection = 0.3 in.)

As the load reached 16.0 kips (0.3 in. deflection) another flexural crack was observed at the South side at Stn. 47. This crack inclined diagonally towards the South side point load grew in width with further loading while other flexural cracks propagated comparatively slower with increasing loads.

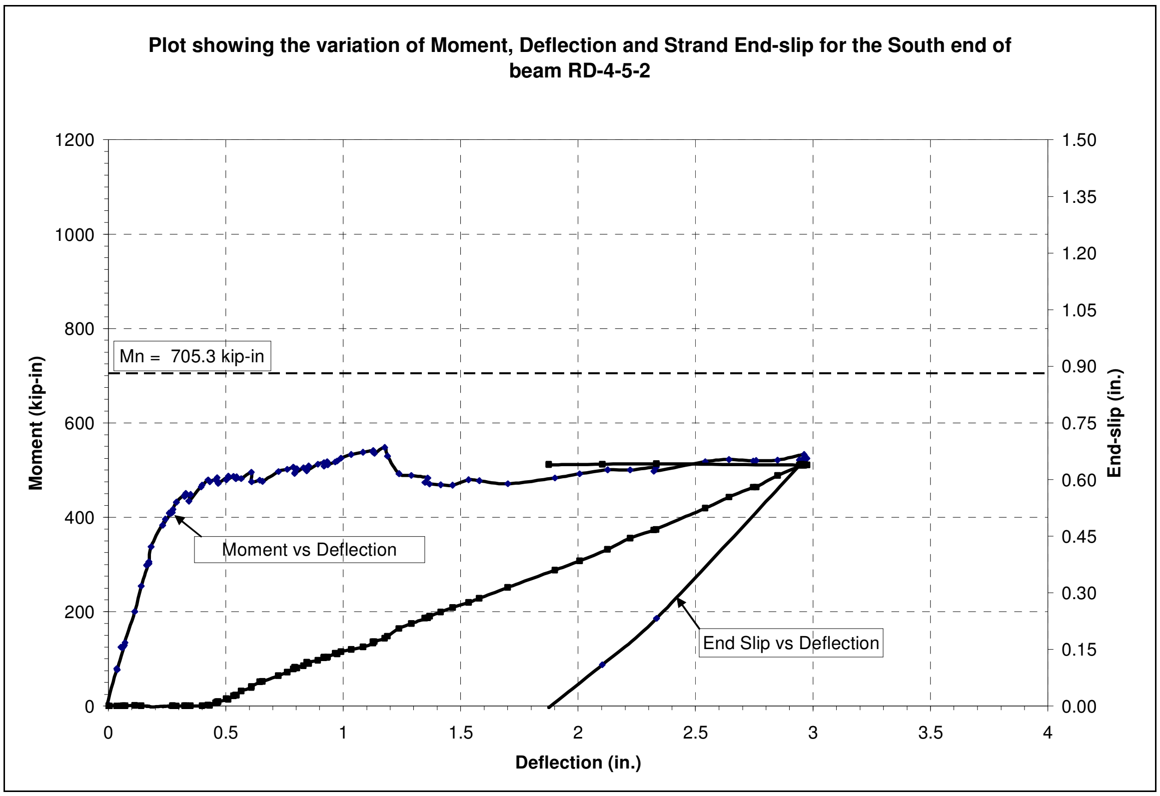
First end-slip of 0.01 in. was noted at 18.2 kips (0.5 in. deflection) and gradually increased with every load increment.

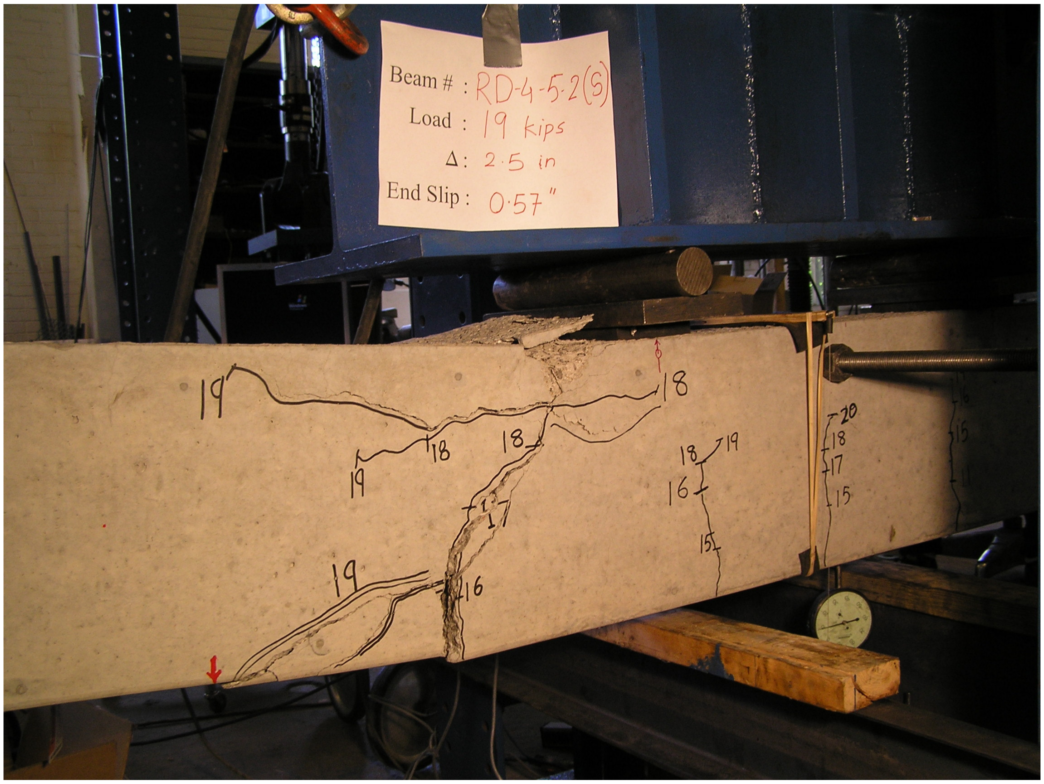
At 18.4 kips and deflection of 1.2 in. cracks were audible. Concrete above the topmost location of the inclined flexural crack started showing signs of crushing as it moved out of the top surface at the load of 17.8 in. (1.4 in deflection).Spalling of concrete at the same location started at this load and continued with increasing loads.

At the load of 19.3 kips (2.5 in. deflection) the beam gave a sudden jerk and concrete crushing was observed at the location where the inclined flexural crack reached its topmost point. This demonstrated the Bond failure. Maximum end-slip was 0.57 in.

End-slip at the North end remained 0.00 in. throughout the loading cycle.

There were 7 cracks in the middle 58 in. span with average crack spacing of 9.7 in. An inclined flexural crack was noticed at Stn. 47 which later bifurcated (approx. 4 in from the bottom) to Stn. 38.





Cracking pattern for Beam RD-4-5-2 being loaded at South end

BEAM NAME: RD-6-5-1
END: NORTH
DATE: 07/26/2005

TEST PARAMETERS	
Concrete Compressive Strength	**8500 psi**
Embedment Length(L_e)	**73 in.**
Span	**162 in.**
Failure Mode	**Flexure**
Maximum Load	**23.1 kips**
Maximum Moment	**797 kip-in**
Deflection @ Failure	**2.5 in.**
Rebound after complete unloading	**1.8 in.**
Average Transfer Length (L_t) @ release	**30.0 in.**
@ time of testing	**49.8 in.**
Average NASP P.O value for strand "D"	**6.89 kips**

<u>TEST SUMMARY</u>

Load was applied in approximately 1.5 kips increments till first flexural cracking. Beyond this point the deflection was incremented by 0.03 in. till total deflection reached 1.00 in. Further increments of deflection were kept 0.05 in. up to 2.0 in. From this point till failure deflection increments were set to 0.1 in.

First flexural crack was observed at 12.8 kips at deflection of 0.3 in. Initially three cracks were noted at two point loads and at approximately midpoint of the two load points.

As the load reached 18.5 kips (0.9 in deflection), first end-slip of 0.004 in. was noted. At the same load and deflection, a diagonally inclined flexural crack was observed rising from two points located at Stn. 38 and Stn. 35 from the North end and joining at 2.5 in. from bottom surface to form a single crack.

With the values of load going beyond 21.7 kips (deflection 1.7 in.), the first flexural crack from North end appeared to increase in width. Finally at the load of 23.1 kips (deflection 2.5 in. ; max end-slip = 0.06 in.) concrete crushing failure was seen at the top surface of concrete.

Values of end-slip gradually went on increasing with load and deflection until concrete crushing failure occurred. At failure end-slip reading on the South end was 0.0015 in.

Since the concrete crushing occurred at the location of strain potential device, deflection readings for unloading cycle could not be noted. However, after complete unloading, deflection at 0.0 kips was noted using a dial gauge (deflection reading after complete unloading = 0.7 in.).

Cracking pattern included 11 cracks in the middle 59 in. span with average crack spacing of 5.9 in. An inclined flexural was noticed at Stn. 38

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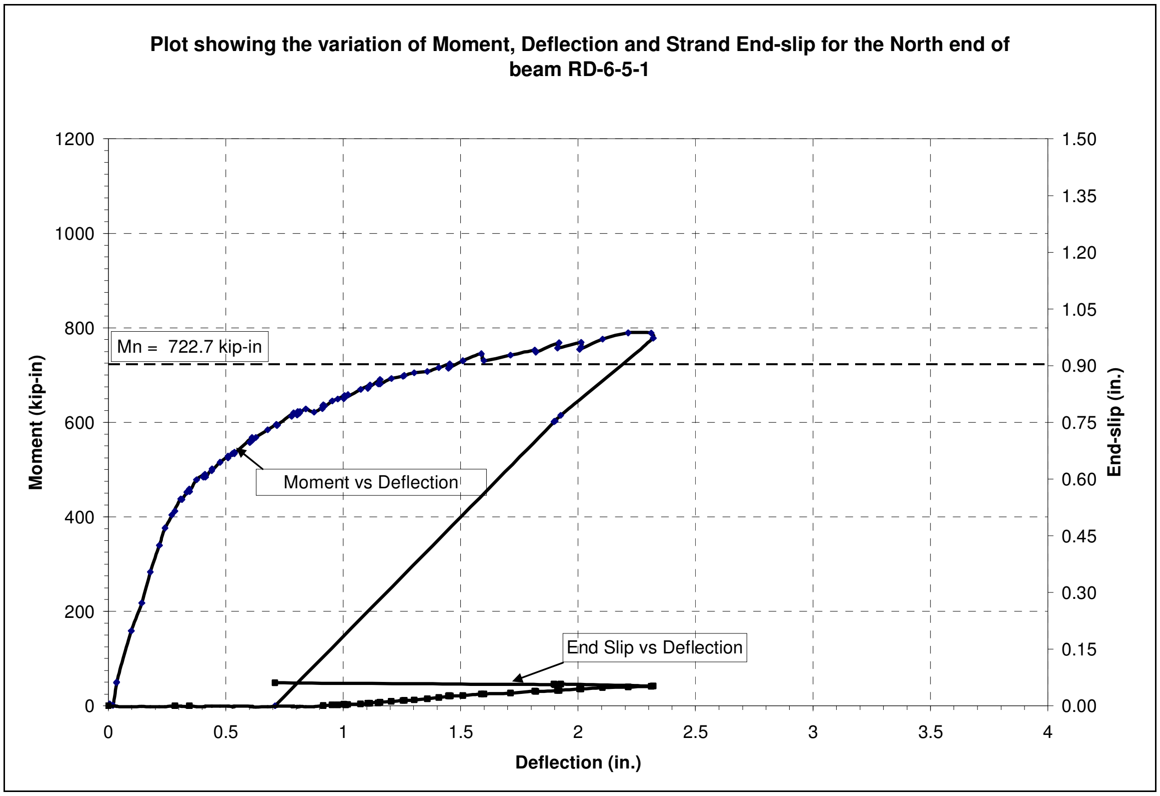
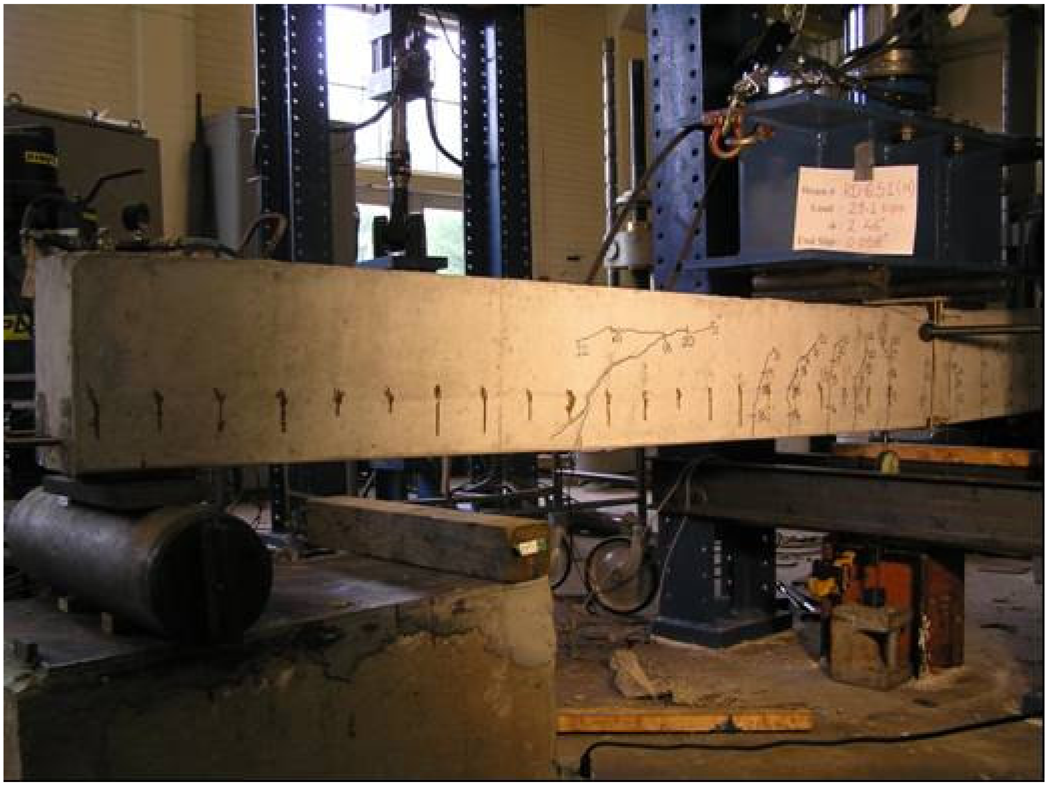




Cracking pattern for Beam RD-6-5-1 being loaded at North end.

BEAM NAME: RD-6-5-1
END: SOUTH
DATE: 07/27/2005

TEST PARAMETERS	
Concrete Compressive Strength	**8500 psi**
Embedment Length(L_e)	**58 in.**
Span	**132 in.**
Failure Mode	**Flexure**
Maximum Load	**29.2 kips**
Maximum Moment	**788 kip-in**
Deflection @ Failure	**2.0 in.**
Rebound after complete unloading	**1.3 in.**
Average Transfer Length (L_t) @ release	**28 in.**
@ time of testing	**45.3 in.**
Average NASP P.O value for strand "D"	**6.89 kips**

TEST SUMMARY

Load was applied in approximately 2 kips increments till first flexural cracking. Beyond this point the deflection was incremented by 0.03 in. till total deflection reached 1.00 in. Further increments of deflection were kept 0.05 in. up to 2.0 in. From this point till failure deflection increments were set to 0.1 in.

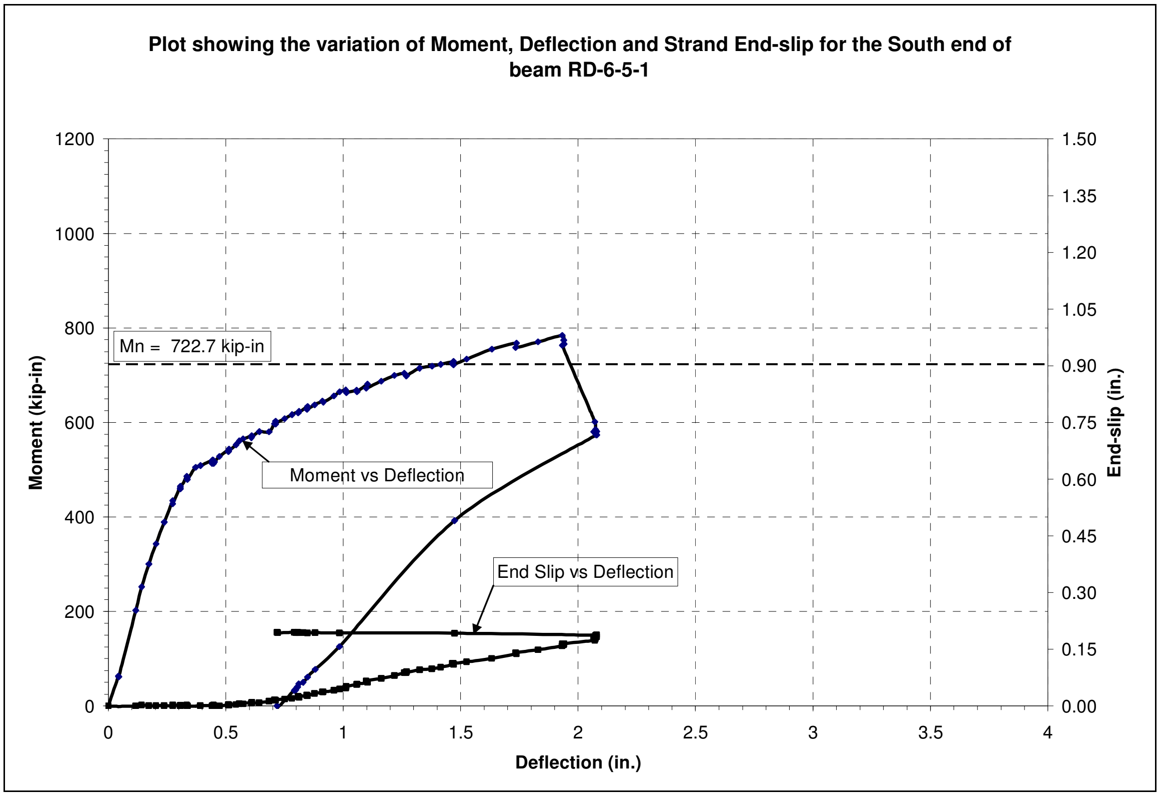
First flexural crack was observed at 17.2 kips at deflection of 0.3 in. Initially three cracks were noted at two point loads and at approximately midpoint of the two load points.

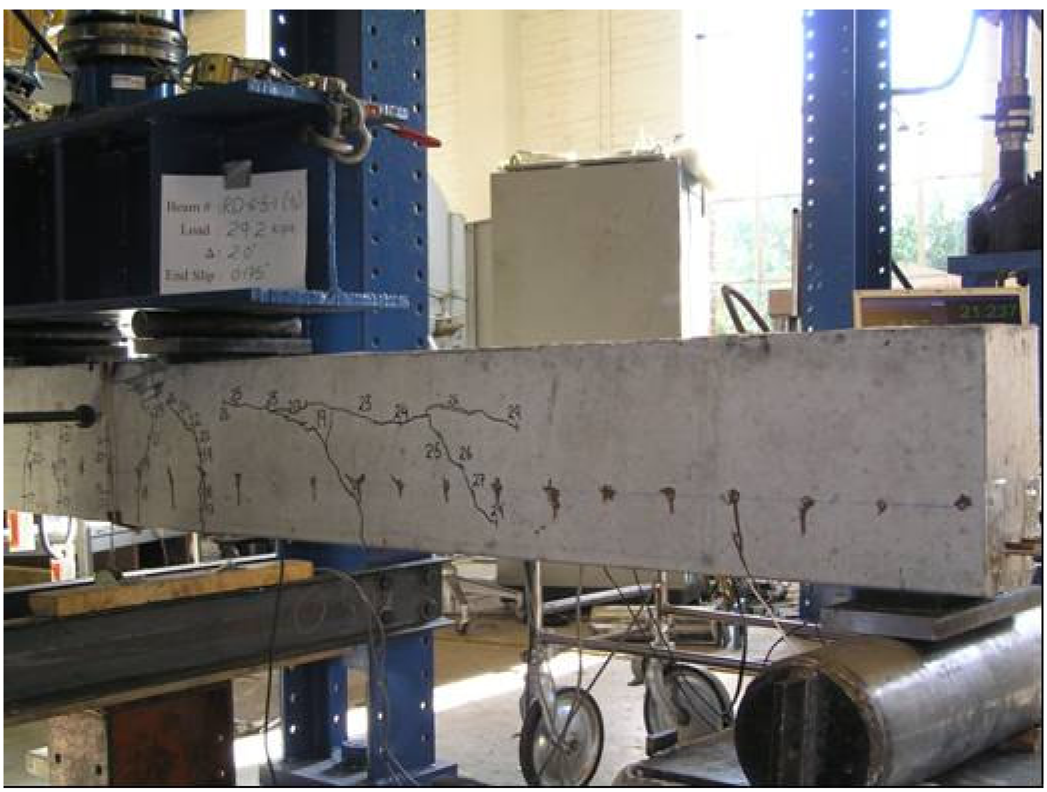
As the load reached 19.5 kips (0.4 in. deflection) a large inclined flexural crack was discovered at Stn. 39. First end-slip was noted as 0.006 in. at the first subsequent increment when load was 19.8 kips (deflection = 0.5 in.).

Cracks became audible at the load of 25.8 kips (1.2 in. deflection). End-slip at the load of 28.8 kips occurred with a clicking sound near the South end.

Concrete crushing failure was noted at the top surface of concrete at the load of 29.2 kips (deflection = 2.0 in.) Maximum end-slip noted at South end was 0.18in. The end-slip reading at the North end remained 0.00 in.

Cracking pattern shows 5 cracks in the middle 25 in. span with average crack spacing of 6.3 in. An inclined flexural crack was observed at Stn. 41. This crack went on to form a crack similar to another inclined flexural crack which did not reach the bottom surface. Distance between these two similar cracks was 16.5 in.





Cracking pattern for Beam RD-6-5-1 being loaded at South end.

BEAM NAME: RD-6-5-2
END: NORTH
DATE: 07/27/2005

TEST PARAMETERS	
Concrete Compressive Strength	**8500 psi**
Embedment Length(L_e)	**73 in.**
Span	**162 in.**
Failure Mode	**Flexure**
Maximum Load	**21.3 kips**
Maximum Moment	**735 kip-in**
Deflection @ Failure	**2.0 in.**
Rebound after complete unloading	**1.7 in.**
Average Transfer Length (L_t) @ release	**25.6 in.**
@ time of testing	**44.2 in.**
Average NASP P.O value for strand "D"	**6.89 kips**

TEST SUMMARY

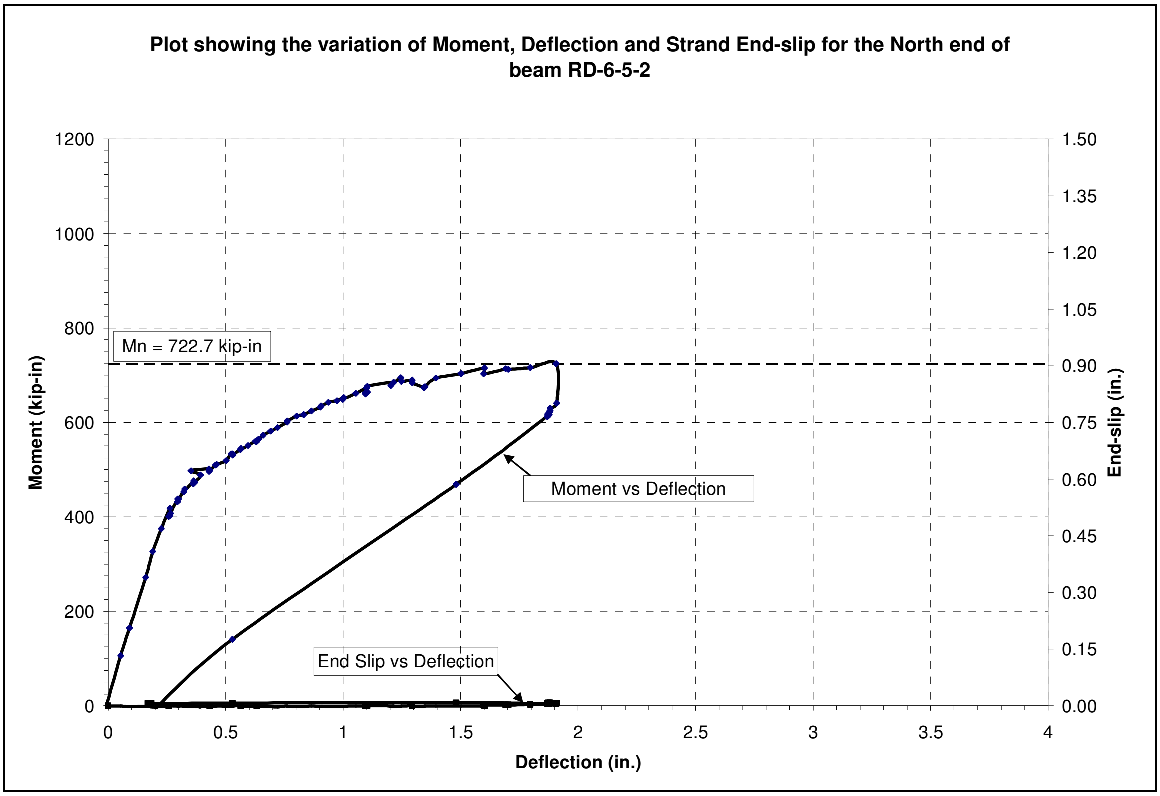
Load was applied in approximately 1.5 kips increments till first flexural cracking. Beyond this point the deflection was incremented by 0.03 in. till total deflection reached 1.00 in. Further increments of deflection were kept 0.05 in. up to 2.0 in. From this point till failure deflection increments were set to 0.1 in.

First flexural crack was observed at 12.3 kips at deflection of 0.27 in. Initially three cracks were noted at two point loads and at approximately midpoint of the two load points.

Cracks became audible at the load of 20.3 kips (deflection = 1.3 in.) and an inclined flexural crack was seen with a sudden cracking sound at the load of 20.6 kips (deflection = 1.4 in.) located at the Stn. 36.

First end-slip of 0.004 in. was noted at the load of 21.3 kips (1.6 in. deflection). As the load reached 21.3 kips (deflection 2.0 in.) concrete crushing failure was observed at the top surface. The maximum end-slip at failure = 0.01 in.

Cracking pattern included 8 cracks in the middle 56 in. span with average crack spacing of 8 in. Also an inclined flexural crack was noticed at Stn. 36.



Cracking pattern for Beam RD-6-5-2 being loaded at North end.

BEAM NAME: RD-6-5-2
END: SOUTH
DATE: 07/27/2005

TEST PARAMETERS	
Concrete Compressive Strength	**8500 psi**
Embedment Length(L_e)	**58 in.**
Span	**132 in.**
Failure Mode	**Bond Failure**
Maximum Load	**26.8 kips**
Maximum Moment	**724 kip-in**
Deflection @ Failure	**2.0 in.**
Rebound after complete unloading	**1.3 in.**
Average Transfer Length (L_t) @ release	**29.2 in.**
@ time of testing	**48.3 in.**
Average NASP P.O value for strand "D"	**6.89 kips**

<u>TEST SUMMARY</u>

Load was applied in approximately 2 kips increments till first flexural cracking. Beyond this point the deflection was incremented by 0.03 in. till total deflection reached 1.00 in. Further increments of deflection were kept 0.05 in. up to 2.0 in. From this point till failure deflection increments were set to 0.1 in.

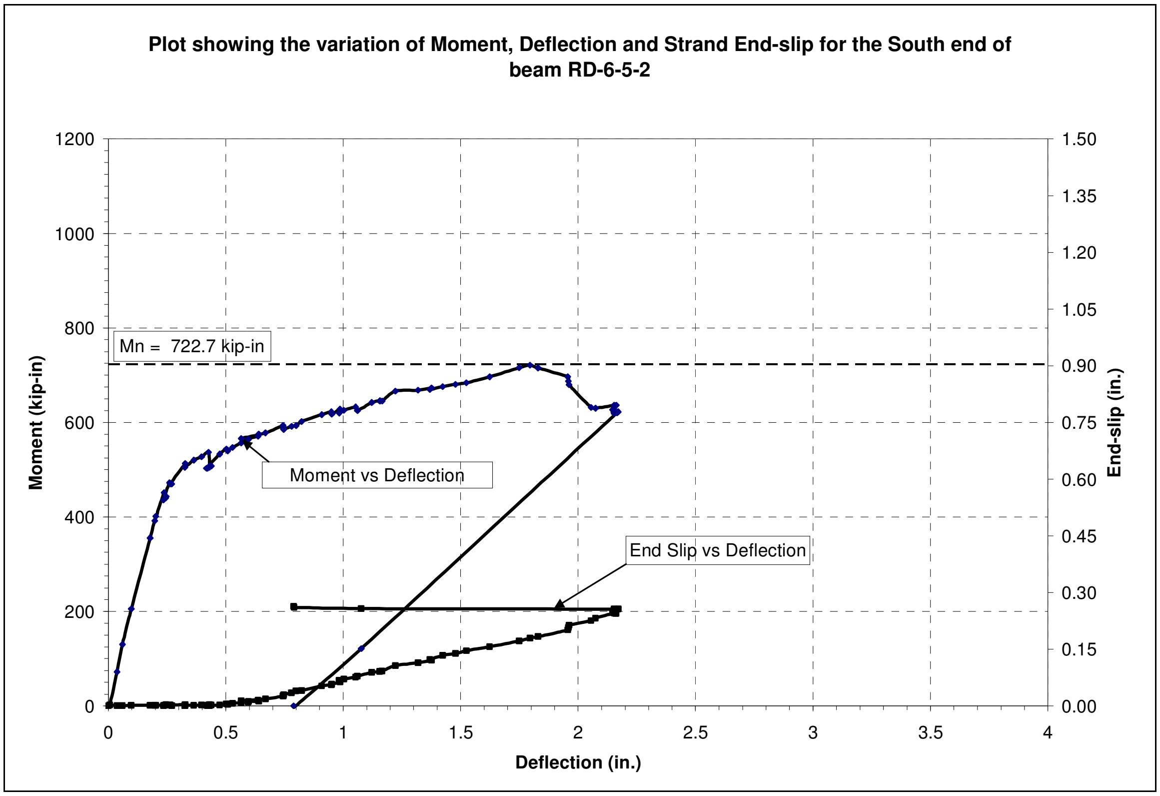
First flexural crack was observed at 16.5 kips at deflection of 0.2 in. Initially only two cracks were observed under the two point loads. Crack at midway between two point loads was discovered at 19.4 kips. (deflection = 0.4 in.)

As the load reached 20.1 kips (0.4 in deflection), a diagonally inclined flexural crack was observed rising from Stn. 38. First end-slip of 0.03 in. was noted at the load of 21.3 kips.

Cracks were audible at the load of 23.4 kips (deflection 1.0 in.). Cracking became louder at the load of 26.8 kips (1.8 in. deflection) finally concrete crushing failure was noted at the deflection of 2.0 in.

Throughout the loading cycle, end-slip remained 0.00 in. at both ends.

Cracking pattern included 7 cracks in the middle 38 in. span with average crack spacing of 6.3 in. Also an inclined flexural crack was noticed at Stn. 38.



Cracking pattern for Beam RD-6-5-2 being loaded at South end.

BEAM NAME: RD-6A-5-1
END: NORTH
DATE: 08/02/2005

TEST PARAMETERS	
Concrete Compressive Strength	**11420 psi**
Embedment Length(L_e)	**73 in.**
Span	**162 in.**
Failure Mode	**Flexure**
Maximum Load	**23 kips**
Maximum Moment	**794 kip-in**
Deflection @ Failure	**2.3 in.**
Average Transfer Length (L_t) @ release	**35.4 in.**
@ time of testing	**39.9 in.**
Average NASP P.O value for strand "D"	**6.89 kips**

TEST SUMMARY

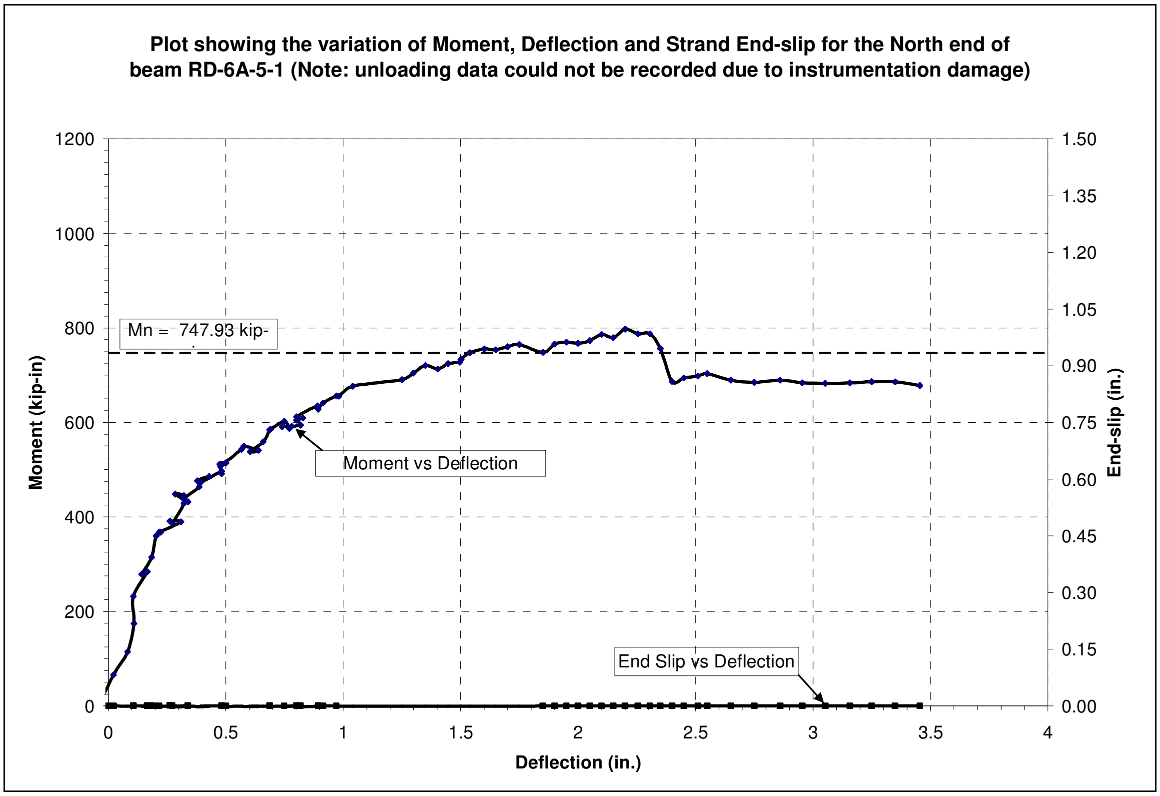
Load was applied in approximately 2.5 kips increments till first flexural cracking. Beyond this point the deflection was incremented by 0.03 in. till total deflection reached 1.00 in. Further increments of deflection were kept 0.05 in. up to 2.0 in. From this point till failure deflection increments were set to 0.1 in.

First flexural crack was observed at 10.8 kips at deflection of 0.2 in. The ext flexural cracks were observed in pairs at 13.3 kips (deflection 0.5 in.) and 13.8 kips (deflection 0.5 in.).

While the loading was in progress (at 18.5 kips, deflection 1.1 kips) the electronic readings for deflection were not consistent with the dial gauge readings. By inspection it was clear that the strain potential readings were incorrect. Graphs plotted include manually noted points beyond this load and deflection.

Concrete cracks were audible and small pieces of concrete started spalling from the concrete surface at the load of 23 kips (deflection = 2.2 in.) and finally at same load and deflection of 2.3 in. concrete crushing failure was noted at the top surface of the concrete.

End-slip readings at both ends were 0.00 throughout loading and unloading of the beam. Cracking pattern included 10 cracks in the middle 66 in span with average crack spacing of 6.6 in. First flexural crack was at 51 in from the North end.



Cracking pattern for Beam RD-6A-5-1 being loaded at North end.

BEAM NAME: RD-6A-5-1
END: SOUTH
DATE: 08/03/2005

TEST PARAMETERS	
Concrete Compressive Strength	**11420 psi**
Embedment Length(L_e)	**58 in.**
Span	**132 in.**
Failure Mode	**Flexure**
Maximum Load	**29.8 kips**
Maximum Moment	**805 kip-in**
Deflection @ Failure	**2.5 in.**
Rebound after complete unloading	**2.0 in.**
Average Transfer Length (L_t) @ release	**29.10 in.**
@ time of testing	**37.16 in.**
Average NASP P.O value for strand "D"	**6.89 kips**

TEST SUMMARY

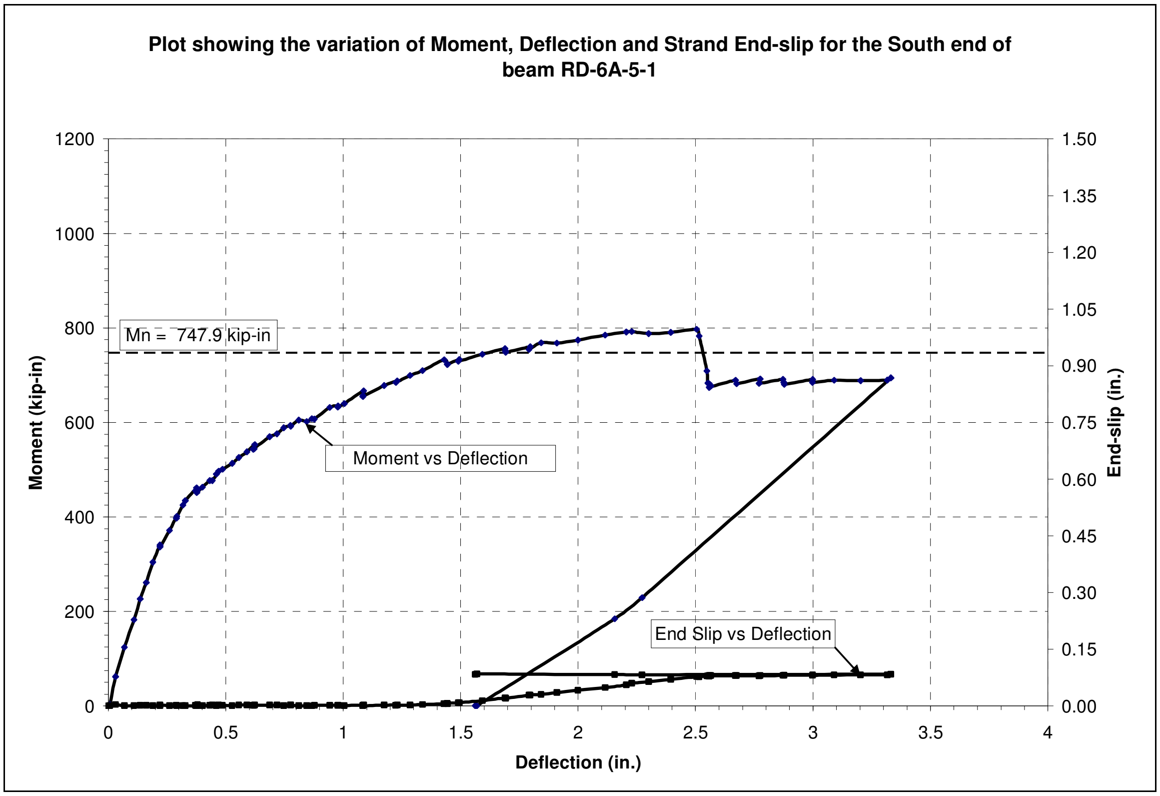
Load was applied in approximately 2 kips increments till first flexural cracking. Beyond this point the deflection was incremented by 0.03 in. till total deflection reached 1.00 in. Further increments of deflection were kept 0.05 in. up to 2.0 in. From this point till failure deflection increments were set to 0.1 in.

First flexural crack was observed at 17.0 kips at deflection of 0.4 in. First flexural cracks occurred in two pairs symmetrically about the two point loads.

Cracks became audible at the load of 26.3 kips (deflection 1.4 in.). First end-slip of 0.005 in. was noted at 26.6 kips (deflection 1.4 in.). End-slip readings went on increasing gradually from this point up to failure.

Concrete crushing failure was observed at 29.8 kips at the deflection of 2.5 in. end-slip reading at failure = 0.083 in. End-slip at the North end remained 0.000 in.

Pattern of cracks demonstrates 8 cracks in the middle 51 in. span with average spacing = 6.4 in. First flexural crack was seen at 45 in. from the South end. No inclined flexural crack was noticed. Crack width of the central crack was 3/8th in. while width of the outermost cracks = ¼ in each.



Cracking pattern for Beam RD-6A-5-1 being loaded at South end.

BEAM NAME: RD-6A-5-2
END: NORTH
DATE: 08/03/2005

TEST PARAMETERS	
Concrete Compressive Strength	**11420 psi**
Embedment Length(L_e)	**73 in.**
Span	**162 in.**
Failure Mode	**Flexure**
Maximum Load	**22.6 kips**
Maximum Moment	**780 kip-in**
Deflection @ Failure	**3.0 in.**
Rebound after complete unloading	**2.5 in.**
Average Transfer Length (L_t) @ release	**20.5 in.**
@ time of testing	**32.4 in.**
Average NASP P.O value for strand "D"	**6.89 kips**

TEST SUMMARY

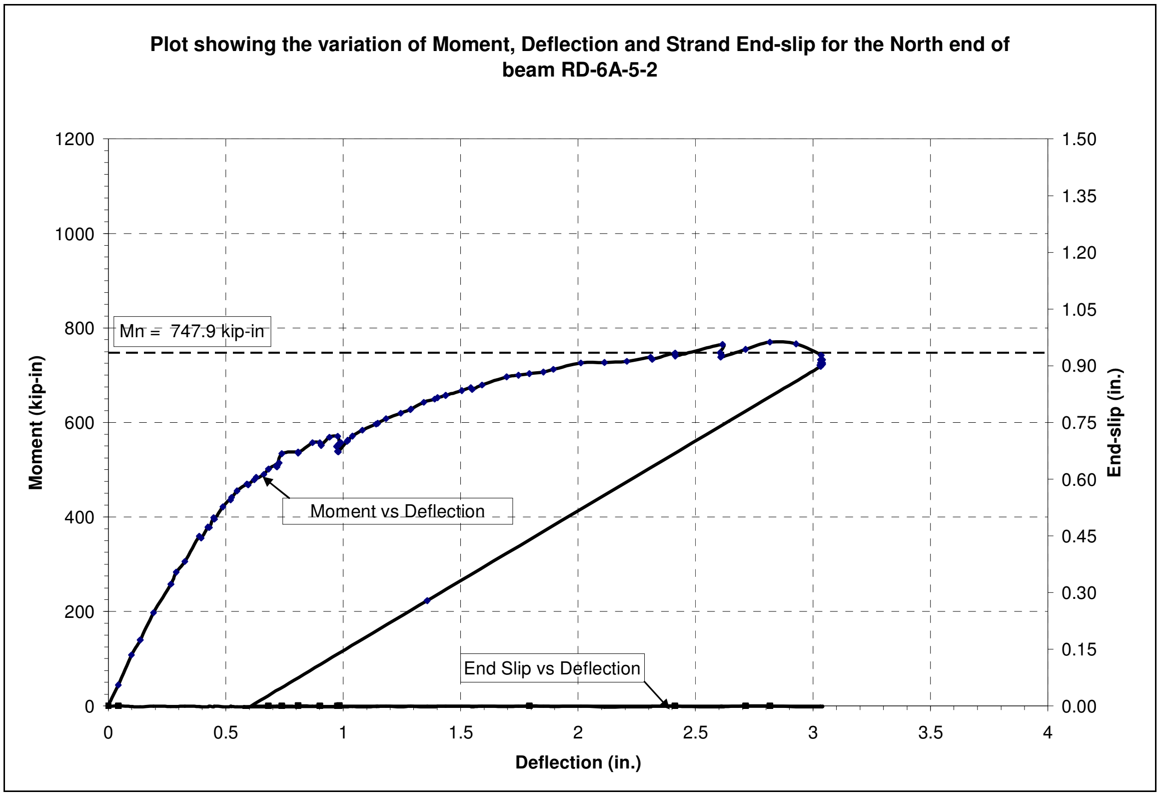
Load was applied in approximately 1.0 kip increments till first flexural cracking. Beyond this point the deflection was incremented by 0.03 in. till total deflection reached 1.00 in. Further increments of deflection were kept 0.05 in. up to 2.0 in. From this point till failure deflection increments were set to 0.1 in.

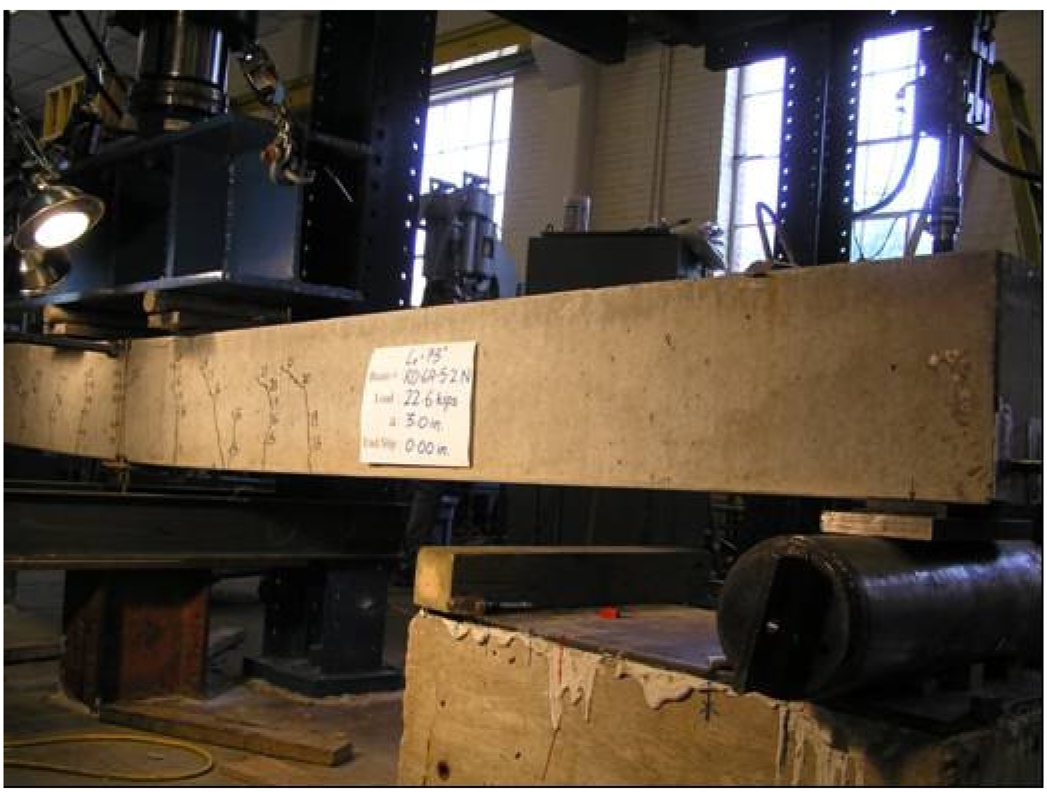
First flexural crack was observed at 11.1 kips at deflection of 0.4 in. Initially only a single crack was observed. More pronounced flexural cracks (formed in pairs and symmetrically about the two point loads) at the load of 15.0 kips. (deflection 0.7 in.)

At approximately 16.4 kips (deflection = 1.0 in.) Concrete started spalling from the earlier existing crushed zone (formed during South end testing). The value of load was slightly decreased at this point and increased again gradually hereafter.

Concrete crushing failure was noticed at the load of 22.6 kips (deflection = 3.1 in.) End-slip readings at both ends remained 0.000 in.

Cracking pattern included 8 cracks in the middle 52 in. span. No inclined flexural crack was noticed in the shear zone. First flexural crack was at Stn. 52 from the North end.





Cracking pattern for Beam RD-6A-5-2 being loaded at North end

BEAM NAME: RD-6A-5-2
END: SOUTH
DATE: 08/03/2005

TEST PARAMETERS	
Concrete Compressive Strength	**11420 psi**
Embedment Length(L_e)	**58 in.**
Span	**132 in.**
Failure Mode	**Flexure**
Maximum Load	**28.8 kips**
Maximum Moment	**778 kip-in**
Deflection @ Failure	**1.9 in.**
Rebound after complete unloading	**1.8 in.**
Average Transfer Length (L_t) @ release	**20.1 in.**
@ time of testing	**40.1 in.**
Average NASP P.O value for strand "D"	**6.89 kips**

TEST SUMMARY

Load was applied in approximately 2.5 kips increments till first flexural cracking. Beyond this point the deflection was incremented by 0.03 in. till total deflection reached 1.00 in. Further increments of deflection were kept 0.05 in. up to 2.0 in till failure.

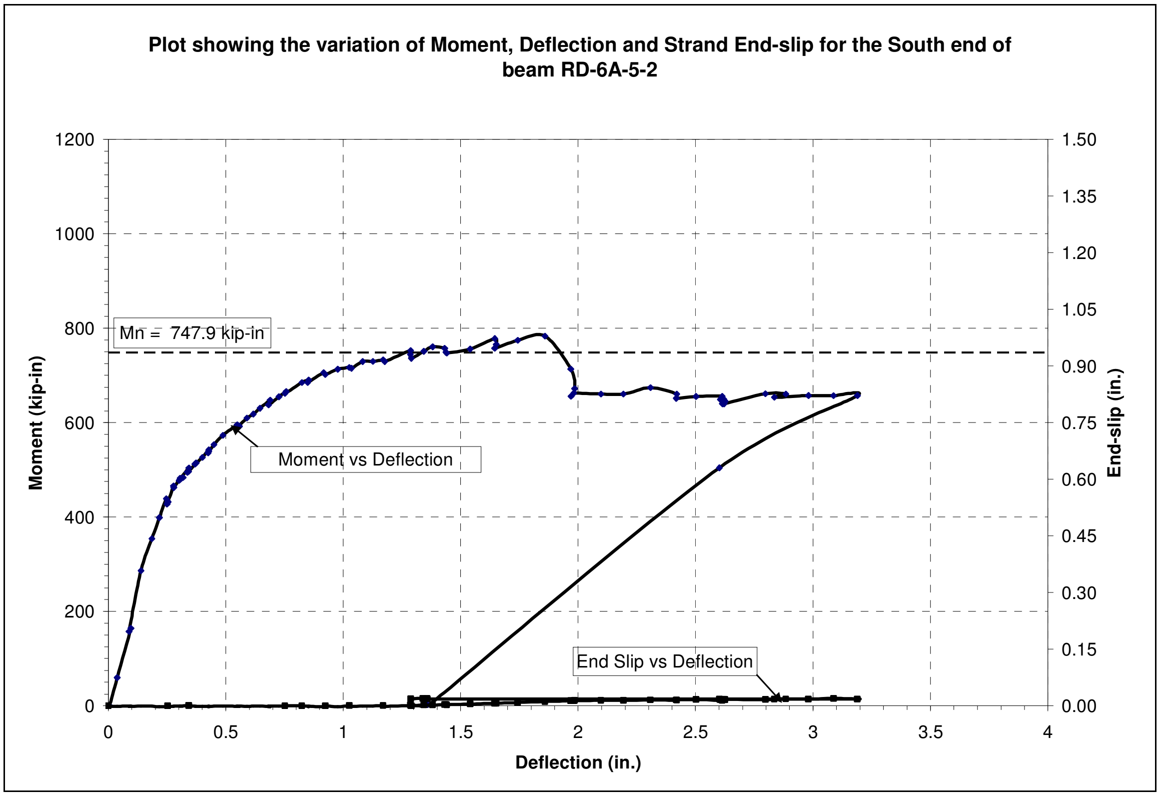
First flexural crack was observed at 16.4 kips at deflection of 0.2 in.

Cracks became audible at the load of 27.5 kips (deflection = 1.3 in.). First end-slip was noted 28 kips. (deflection = 1.5 in.). All further increments of deflection resulted in cracks producing louder and louder sound.

Finally concrete crushing failure was noticed with loud cracking noise at 28.8 kips (deflection = 1.9 in.).End-slip at failure = 0.021 in. Deflection was continued to be incremented till total deflection reached 3.0 in. and then the beam was unloaded.

Cracking pattern shows 8 cracks formed in the middle 51 in span with average crack spacing = 6.4 in. No inclined flexural crack was observed in the shear zone. First flexural crack from the South end occurred at Stn. 42.

End-slip reading at the North end remained 0.000 in. throughout the complete loading and unloading cycle.



Cracking pattern for Beam RD-6A-5-2 being loaded at South end

BEAM NAME: RD-8-5-1
END: NORTH
DATE: 07/26/2005

TEST PARAMETERS	
Concrete Compressive Strength	**13490 psi**
Embedment Length(L_e)	**73 in.**
Span	**162 in.**
Failure Mode	**Flexure**
Maximum Load	**23.5 kips**
Maximum Moment	**811 kip-in**
Maximum Deflection	**2.6 in.**
Rebound after complete unloading	**1.9 in.**
Average Transfer Length (L_t) @ release	**21.16 in.**
@ time of testing	**19.13in.**
Average NASP P.O value for stand "D"	**6.89 kips**

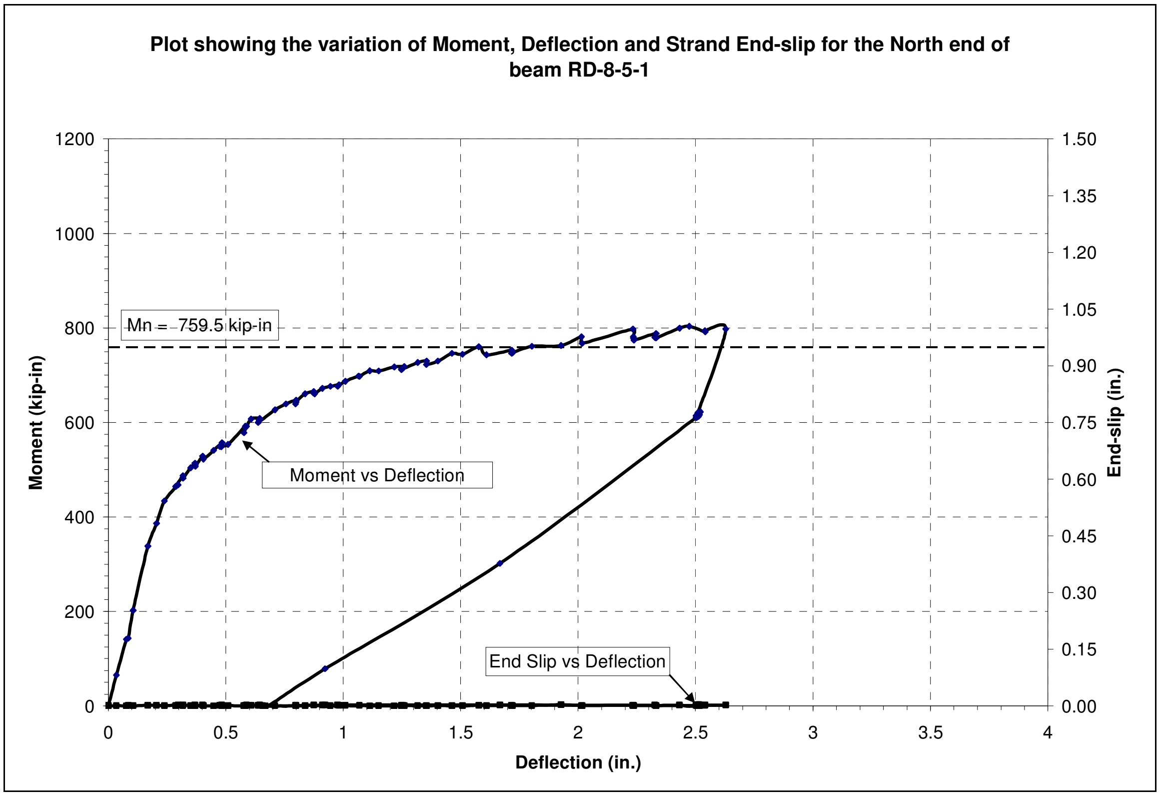
TEST SUMMARY

Load was applied in approximately 2 kips increments till first flexural cracking. Beyond this point the deflection was incremented by 0.03 in. till total deflection reached 1.00 in. Further increments of deflection were kept 0.05 in. up to 2.0 in. From this point till failure deflection increments were set to 0.1 in.

First flexural crack was observed at 12.7 kips at deflection of 0.3 in. Three cracks were seen originating from bottom surface located under two point loads and one at midway between the two point loads.

At 18.1 kips(0.6 in deflection) a pair of cracks symmetrically located from the point loads was noted and yet another pair of cracks was seen at the load of 19.2 kips (0.8 in deflection) also located in similar manner.

Cracks were audible at 22.4 kips (1.9 in deflection) and finally at 23.5 kips concrete crushing failure was noted at the top surface of the beam. Throughout the loading, the end-slip at both ends remained 0.00 in.



Cracking pattern for Beam RD-8-5-1 being loaded at North end

BEAM NAME: RD-8-5-1
END: SOUTH
DATE: 07/26/2005

TEST PARAMETERS	
Concrete Compressive Strength	**13490 psi**
Embedment Length(L_e)	**58 in.**
Span	**132 in.**
Failure Mode	**Flexure**
Maximum Load	**29.8 kips**
Maximum Moment	**804.6 kip-in**
Maximum Deflection	**2.6 in.**
Rebound after complete unloading	**could not be noted due to instrumentation damage**
Average Transfer Length (L_t) @ release	**20.15 in.**
@ time of testing	**19.41 in.**
Average NASP P.O value for stand "D"	**6.89 kips**

TEST SUMMARY

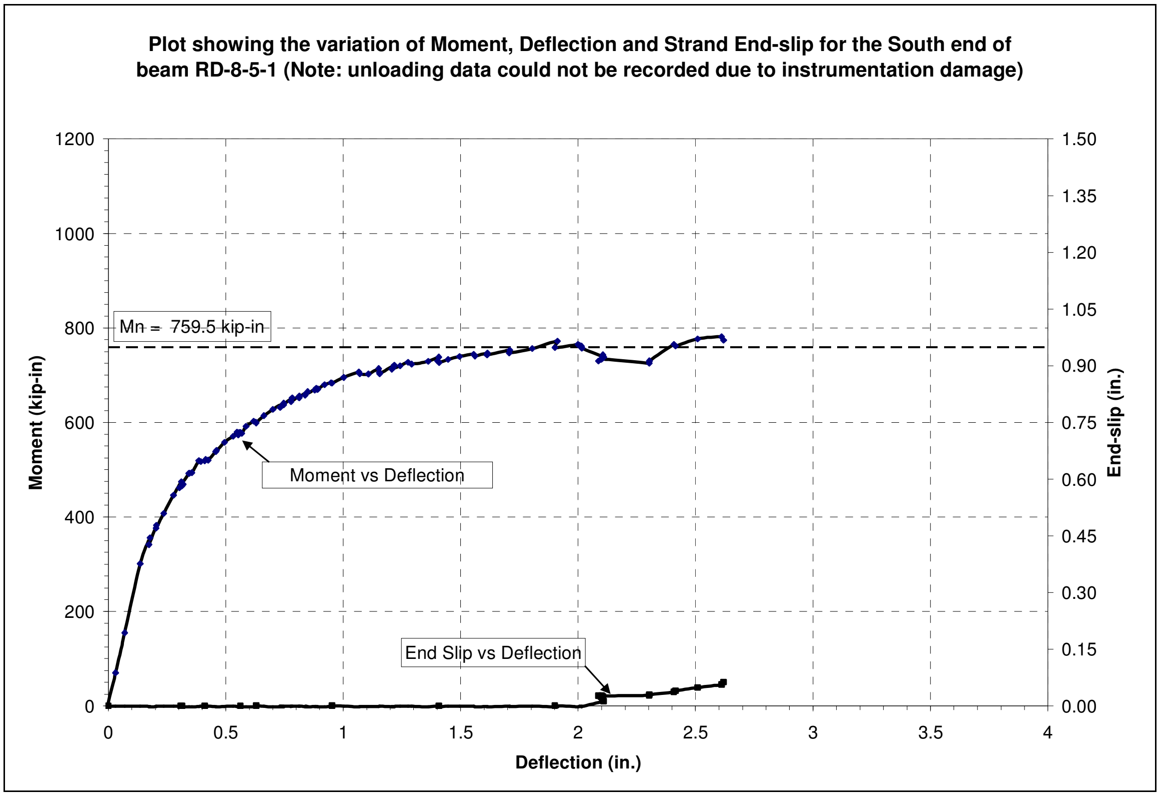
Load was applied in approximately 2 kips increments till first flexural cracking. Beyond this point the deflection was incremented by 0.03 in. till total deflection reached 1.00 in. Further increments of deflection were kept 0.05 in. up to 2.0 in. From this point till failure deflection increments were set to 0.1 in.

First flexural crack was observed at 18.2 kips at deflection of 0.3 in. first flexural cracks originated from the cracks developed during the test for North end. No cracks were seen at this stage at the south side of the two point loads.

Flexural cracks were audible at the load of 27.1 kips (1.1 in. deflection). The sound of cracks was heard without any visible changes till the load reached 29 kips (1.9 in deflection).

At 29 kips, a large inclined flexural crack was discovered, rising from Stn. 24 and Stn 21 and joining at 3 in. from bottom to form one single crack.

Loading was halted at 29.8 kips (deflection 2.6 in.) since cracking seemed to continue for a longer time at the same load. Suddenly drastic end-slip was noted at this point and approx. 5 seconds later concrete crushing was observed at the top surface. Moment at this load was 105% M_n which suggested flexural failure of the beam.



Cracking pattern for Beam RD-8-5-1 being loaded at South end

BEAM NAME: RD-10-5-1
END: NORTH
DATE: 08/01/2005

TEST PARAMETERS	
Concrete Compressive Strength	**14470 psi**
Embedment Length(L_e)	**58 in.**
Span	**132 in.**
Failure Mode	**Flexure**
Maximum Load	**30.4 kips**
Maximum Moment	**821 kip-in**
Deflection @ Failure	**2.1 in.**
Deflection @ Strand Fracture	**2.9 in.**
Rebound after complete unloading (after crushing failure)	**1.4 in.**
Average Transfer Length (L_t) @ release	**26.0 in.**
@ time of testing	**30.24 in.**
Average NASP P.O value for strand “D”	**6.89 kips**

TEST SUMMARY

Load was applied in approximately 3 kips increments till first flexural cracking. Beyond this point the deflection was incremented by 0.03 in. till total deflection reached 1.00 in. Further increments of deflection were kept 0.05 in. up to 2.0 in. From this point till failure deflection increments were set to 0.1 in.

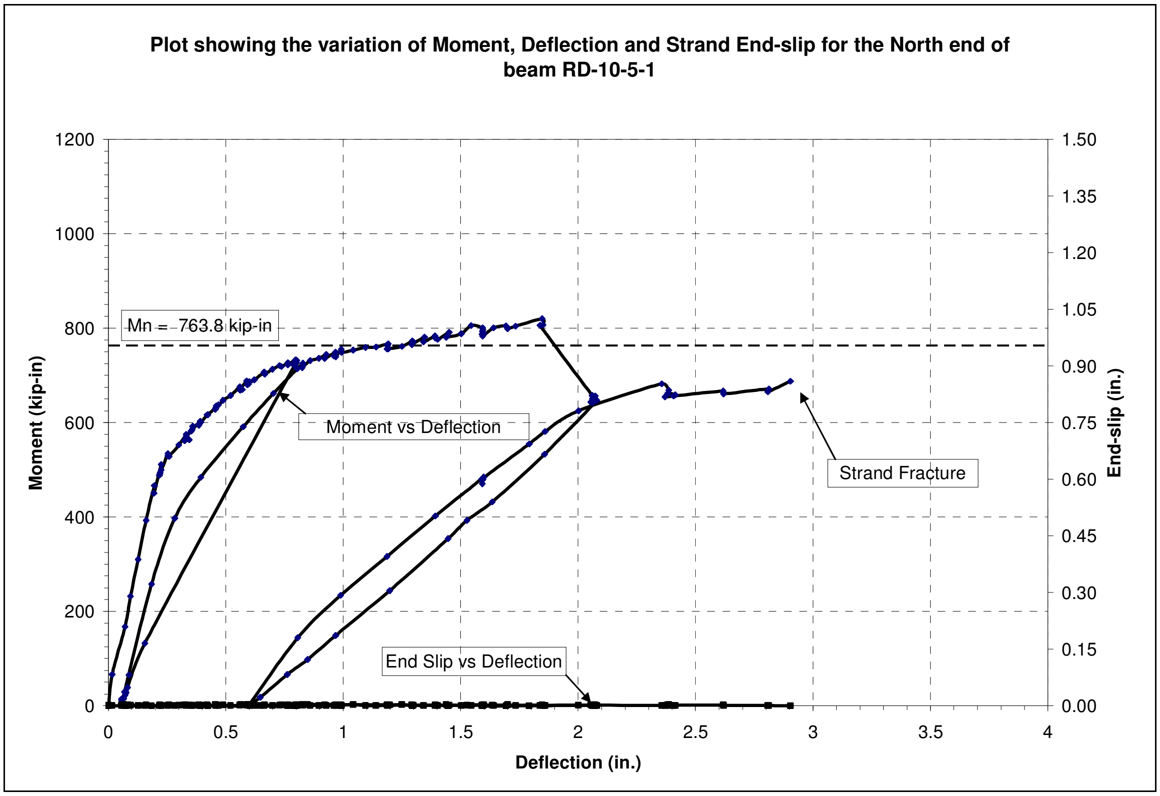
First flexural crack was observed at 19.1 kips at deflection of 0.2 in. Initially four cracks were observed located symmetrically from the center of the span.

As the load reached 21.2 kips (0.3 in deflection), another couple of symmetrically located cracks was seen. Cracks became audible at the load of 26.8 kips. The beam was unloaded at this point to re-adjust the top roller. While reloading the beam for the first time, the increments were set to 0.1 in.

At the laod of 28.4 kips(deflection = 1.2 in.) , a sudden flexural crack was noted at Stn. 41 Finally concrete crushing failure occurred at the load of 30.4 kips. (deflection 2.1 in.)

The beam was completely unloaded and reloaded with an aim to achieve higher deflections than at concrete crushing failure. The deflection increments for the second reloading were set to 0.2 in. Both the strands suddenly broke with a bang at approximately 2.9 in deflection. End slips at both ends remained zero for all loading cycles.

Cracking pattern demonstrated 10 cracks in the middle 58 in. of the beam span with average spacing of cracks 5.8 in.



Cracking pattern for Beam RD-10-5-1 being loaded at North end

BEAM NAME: RD-10-5-1
END: SOUTH
DATE: 08/01/2005

TEST PARAMETERS	
Concrete Compressive Strength	**14470 psi**
Embedment Length(L_e)	**46 in.**
Span	**120 in.**
Failure Mode	**Flexure**
Maximum Load	**39 kips**
Maximum Moment	**819 kip-in**
Deflection @ Failure	**2.6 in.**
Rebound after complete unloading	**1.1 in.**
Average Transfer Length (L_t) @ release	**16.85 in.**
@ time of testing	**27.1 in.**
Average NASP P.O value for strand "D"	**6.89 kips**

<u>TEST SUMMARY</u>

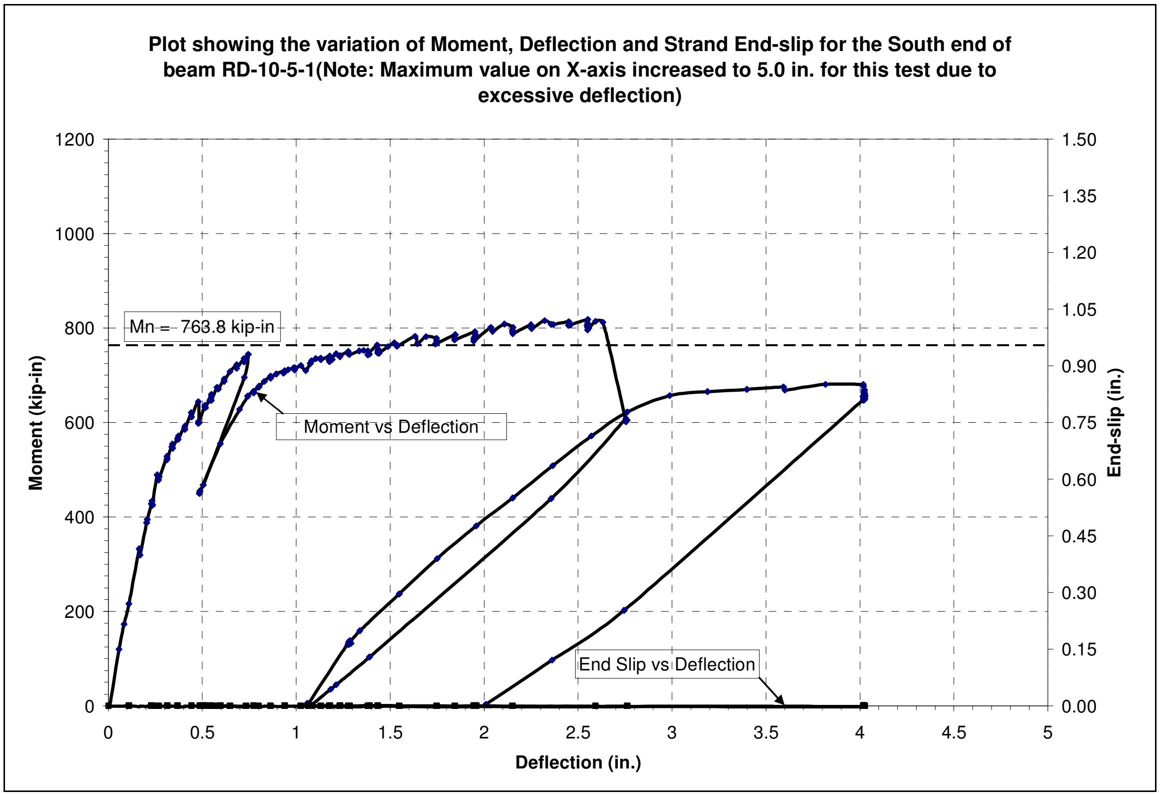
Load was applied in approximately 2.5 kips increments till first flexural cracking. Beyond this point the deflection was incremented by 0.03 in. till total deflection reached 1.00 in. Further increments of deflection were kept 0.05 in. up to 2.0 in. From this point till failure deflection increments were set to 0.1 in.

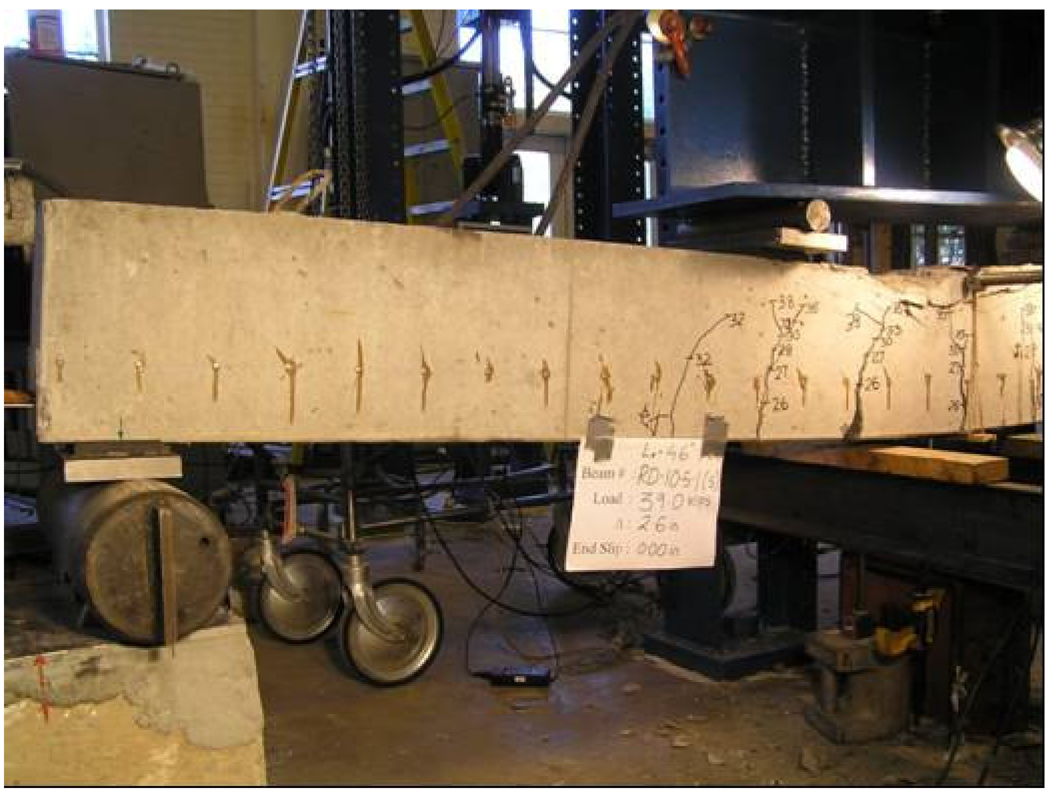
First cracks to be observed for this loading originated from the earlier cracks present on the beam due to the North end testing. New Flexural cracks were observed at 25.7 kips at deflection of 0.3 in. Initially three cracks were noted at two point loads and at approximately midpoint of the two load points.

An inclined flexural crack was noticed with a sudden sound at 25 in from the north support at the load of 30.4 kips. (Deflection = 0.5 in.). At 31.4 kips, the secondary cracks originating from the existing cracks at the north side reached the bottom surface forming another inclined flexural crack at 8 in. from north support.

Concrete spalling began with extended cracking sound at 38.4 kips (deflection 2.3 in.) and suddenly at 39 kips concrete crushing was observed. The load was completely removed and re-applied with an aim of achieving greater deflection. There were no noticeable changes during the second loading cycle. The inclined flexural cracks appear to widen with increasing deflection.

Cracking pattern demonstrated 7 cracks in the middle 48 in. In addition to these flexural cracks, 2 inclined flexural cracks (@ Stn. 8 and Stn. 26) were observed in the shear zone at the North side.





Cracking pattern for Beam RD-10-5-1 being loaded at South endBEAM NAME: RD-10-5-2

END: NORTH
DATE: 08/02/2005

TEST PARAMETERS	
Concrete Compressive Strength	**144701 psi**
Embedment Length(L_e)	**58 in.**
Span	**132 in.**
Failure Mode	**Flexure**
Maximum Load	**29.2 kips**
Maximum Moment	**788.4 kip-in**
Deflection @ Failure	**1.9 in.**
Rebound after complete unloading	**1.6 in.**
Average Transfer Length (L_t) @ release	**14.85 in.**
@ time of testing	**22.0 in.**
Average NASP P.O value for strand "D"	**6.89 kips**

<u>TEST SUMMARY</u>

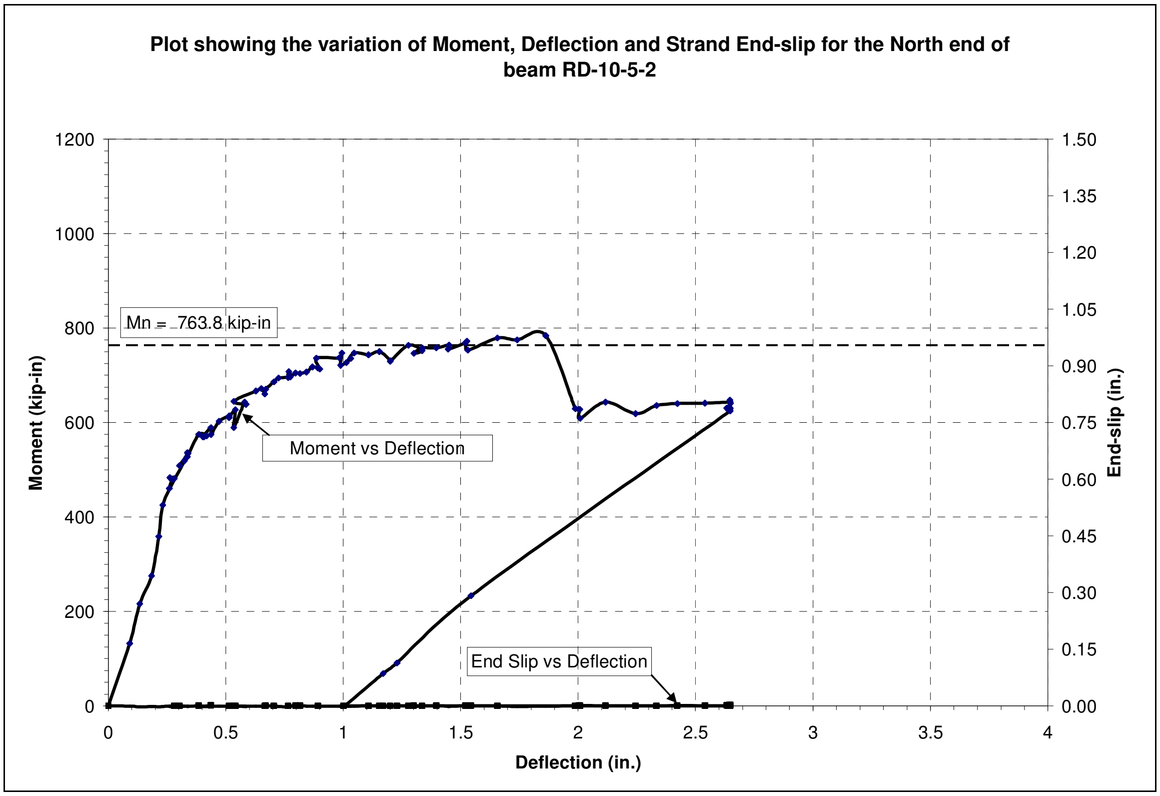
Load was applied in approximately 3 kips increments till first flexural cracking. Beyond this point the deflection was incremented by 0.03 in. till total deflection reached 1.00 in. Further increments of deflection were kept 0.05 in. up to failure.

First flexural crack was observed at 18.6 kips at deflection of 0.2 in. At this load a pair of cracks was seen between the two point loads, the next pair of cracks was observed at load of 20 kips (deflection 0.3 in.)

Cracks became audible at 27.5 kips (deflection = 1.1 in.) The sound became louder and more extended in time at 29.2 kips, waiting for two minutes at the same load and deflection of 1.9 in. resulted in sudden concrete crushing failure at the top surface.

Loading was continued further to achieve higher deflection and finally stopped at deflection = 2.5 in and the beam was unloaded. End slips at both ends remained 0.00 in throughout the loading and unloading cycles.

Crack observed crack pattern included 9 cracks in the middle 53 in span with average spacing of cracks = 5.9 in. No inclined flexural cracks were noted.



Cracking pattern for Beam RD-10-5-2 being loaded at North end

BEAM NAME: RD-10-5-2
END: SOUTH
DATE: 08/02/2005

TEST PARAMETERS	
Concrete Compressive Strength	**14470 ksi**
Embedment Length(L_e)	**46 in.**
Span	**120 in.**
Failure Mode	**Flexure**
Maximum Load	**37.8 kips**
Maximum Moment	**794 kip-in**
Deflection @ Failure	**1.9 in.**
Rebound after complete unloading	**1.6 in.**
Average Transfer Length (L_t) @ release	**18.23 in.**
@ time of testing	**22.03 in.**
Average NASP P.O value for strand "D"	**6.89 kips**

TEST SUMMARY

Load was applied in approximately 4 kips increments till first flexural cracking. Beyond this point the deflection was incremented by 0.03 in. till total deflection reached 1.00 in. Further increments of deflection were kept 0.05 in. till failure and beyond failure it was set to 0.1 in.

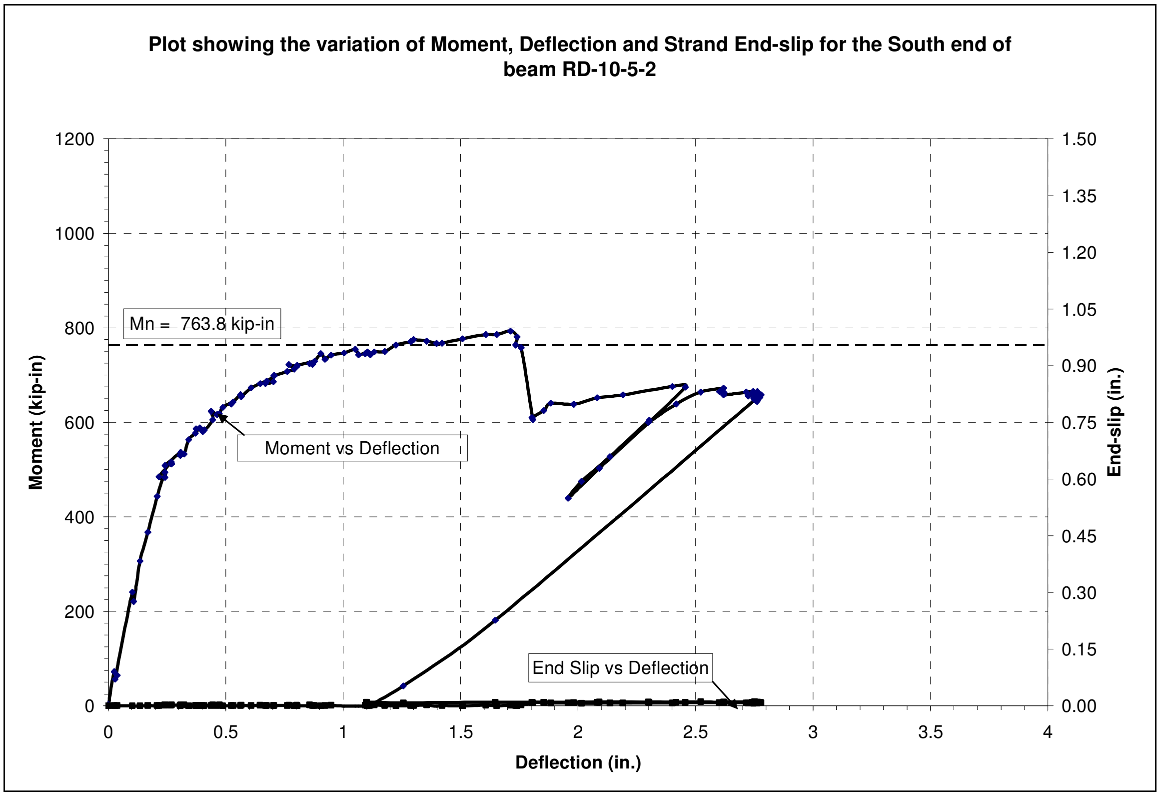
First flexural crack was observed at 24.1 kips at deflection of 0.2 in. Upto load of 25 kips (deflection 0.3 in.) four cracks were noted symmetrically about the two load points and one more flexural crack was noticed at approximately midpoint of the two point loads. at 26 kips. (deflection 0.3 in.)

Cracks became audible from the load of 36.5 kips (deflection 1.5 in.) up to concrete crushing failure which was observed at 37.8 kips. (deflection 1.9 in.) At this point end-slip of 0.013 in was noted at the South end while at North end it was noted as 0.001 in. Both these end-slip readings stayed constant for further loading and unloading cycles.

While applying further load, at approximately 2.3 in deflection, the beam was noticed to be touching the wooden block kept to prevent damage to strain-potentials. Load was reduced by a small amount to remove the wooden block.

Finally loading was stopped at a deflection of 2.6 in. and the beam was unloaded completely.

Cracking pattern included 9 cracks in the middle 58 in. span. No inclined flexural cracks were seen in the shear zone. Width of the central crack was 3/8th in. Location of the first flexural crack from the South end was 37 in.



Cracking pattern for Beam RD-10-5-2 being loaded at South end

APPENDIX B

DEVELOPMENT LENGTH TEST SUMMARIES FOR RECTANGULAR BEAMS WITH STRAND A/B (0.5 IN.)

BEAM NAME: RA-6-5-1
END: NORTH
DATE: 08/04/2005

TEST PARAMETERS	
Concrete Compressive Strength	**8500 psi**
Embedment Length(L_e)	**73 in.**
Span	**162 in.**
Failure Mode	**Flexure**
Maximum Load	**22.9 kips**
Maximum Moment	**790 kip-in**
Deflection @ Failure	**2.1 in.**
Rebound after complete unloading	**2.0 in.**
Average Transfer Length (L_t) @ release	**19.2 in.**
@ time of testing	**33.7 in.**
Average NASP P.O value for strand 0.5 in. "A"	**20.95 kips**

TEST SUMMARY

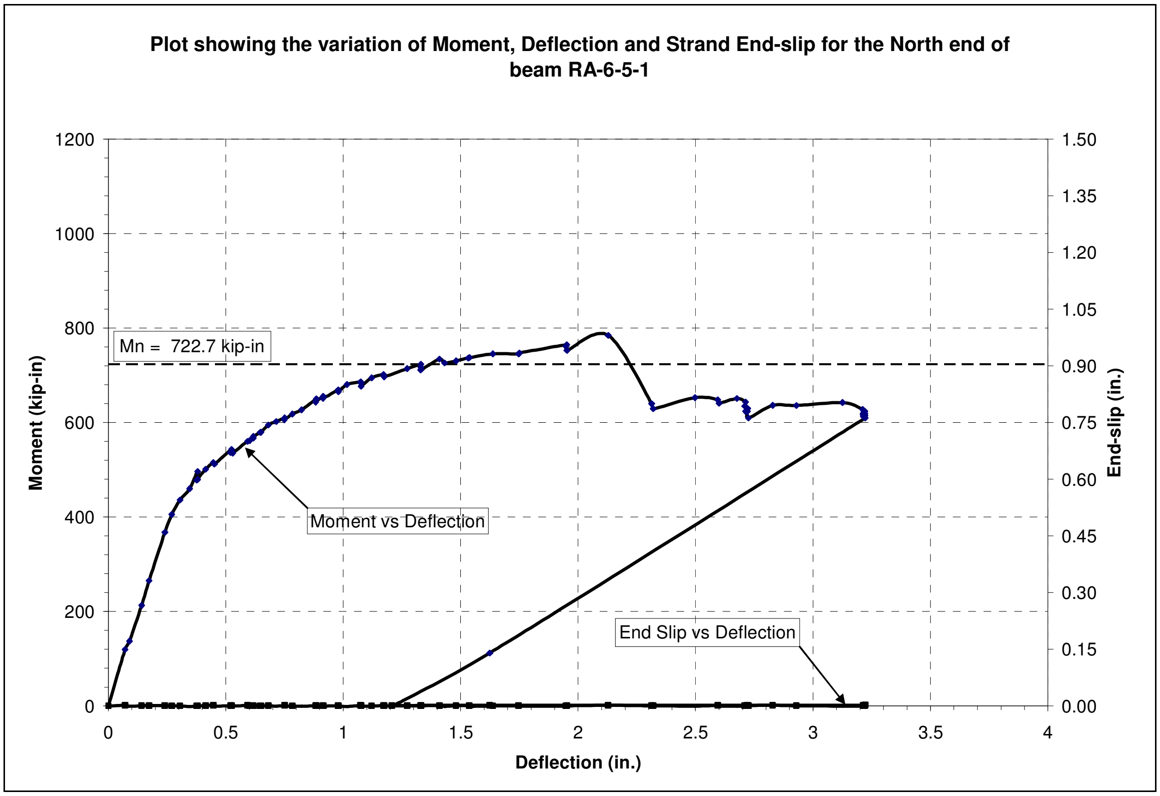
Load was applied in approximately 1.5 kips increments till first flexural cracking. Beyond this point the deflection was incremented by 0.03 in. till total deflection reached 1.00 in. Further increments of deflection were kept 0.05 in. up to 2.0 in. From this point till failure deflection increments were set to 0.1 in.

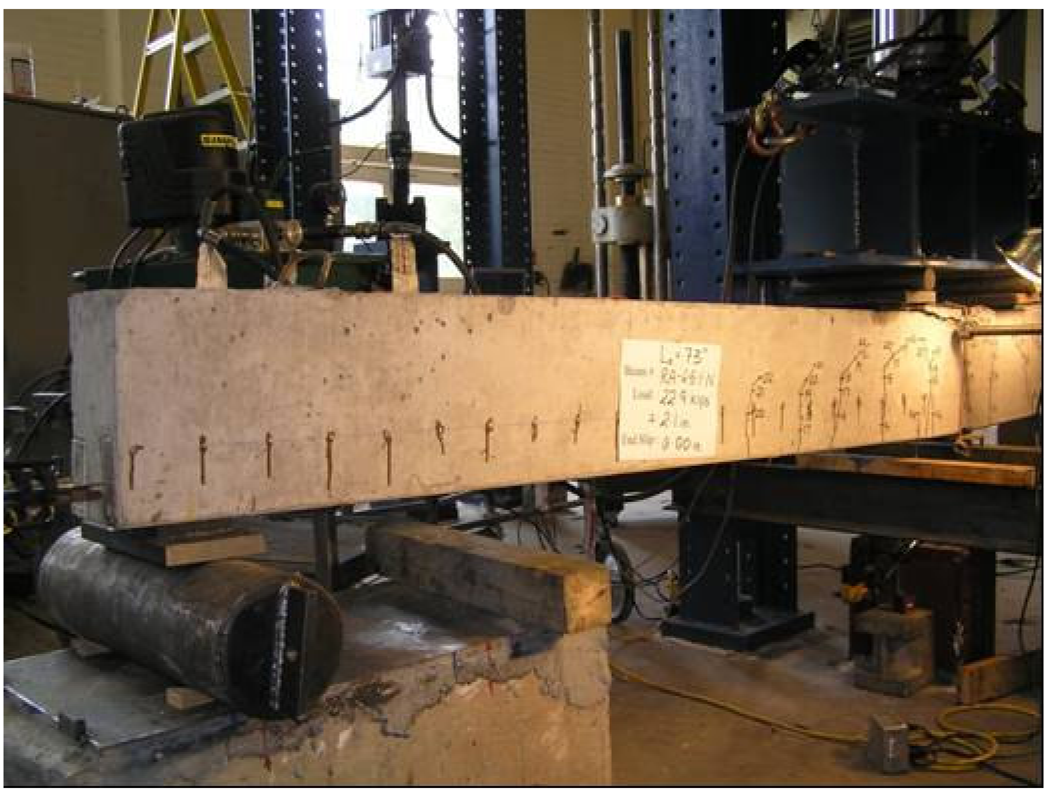
First flexural crack was observed at 13.7 kips at deflection of 0.3 in. Two pairs of symmetrically located cracks were seen at this load and deflection.

As the load reached 22.5 kips (1.9 in deflection), cracks lying between two point loads bifurcated near the top. Cracks were also audible from this and subsequent increments up to failure.

Concrete crushing failure was noted at 22.9 kips. (deflection = 2.1 in.). the beam was continued to be loaded till the deflection reached 3.0 in. End slip at both ends remained 0.000 in. throughout loading and unloading cycles.

Cracking pattern included 11 cracks in the central 66 in. span. First flexural crack was noted at 52 in. from the North support. No inclined flexural crack was observed.





Cracking pattern for Beam RA-6-5-1 being loaded at North end

BEAM NAME: RA-6-5-1
END: SOUTH
DATE: 08/04/2005

TEST PARAMETERS	
Concrete Compressive Strength	**8500 psi**
Embedment Length(L_e)	**58 in.**
Span	**132 in.**
Failure Mode	**Flexure**
Maximum Load	**29.6 kips**
Maximum Moment	**800 kip-in**
Deflection @ Failure	**2.1 in.**
Rebound after complete unloading	**1.9 in.**
Average Transfer Length (L_t) @ release	**18.2 in.**
@ time of testing	**30.0 in.**
Average NASP P.O value for strand 0.5 in. "A"	**20.95 kips**

<u>TEST SUMMARY</u>

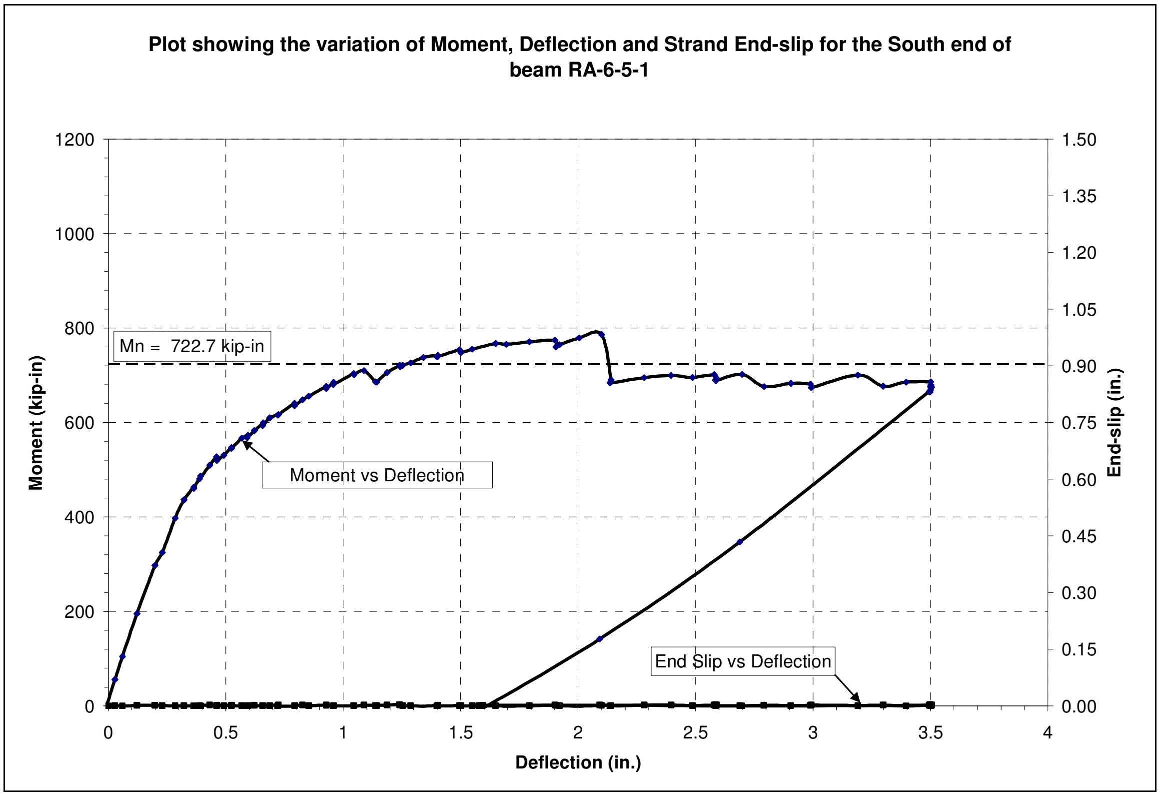
Load was applied in approximately 1.5 kips increments till first flexural cracking. Beyond this point the deflection was incremented by 0.03 in. till total deflection reached 1.00 in. Further increments of deflection were kept 0.05 in. up to 2.0 in. From this point till failure deflection increments were set to 0.1 in.

First flexural crack was observed at 17.5 kips at deflection of 0.4 in. Two pairs of symmetrically located cracks were observed at the subsequent increment (load = 18.2 kips, deflection = 0.4 in.)

At 26.8 kips (deflection = 1.2 in.), concrete already crushed during North end testing started falling off, resulting in slight fluctuation of load. Cracking was audible at 29.1 kips (deflection = 1.9 in.)

Concrete crushing failure was noted at 29.6 kips (deflection = 2.1 in.) at the top surface of the concrete. Beam was loaded till deflection reached 3.5 in and then completely unloaded.

End-slip readings at both ends remained 0.000in. Cracking pattern included 9 cracks in the middle 50 in. span. First flexural crack was located at Stn. 44. No inclined flexural crack was observed.



Cracking pattern for Beam RA-6-5-1 being loaded at South end

BEAM NAME: RA-6-5-2
END: NORTH
DATE: 08/05/2005

TEST PARAMETERS	
Concrete Compressive Strength	**8500 psi**
Embedment Length(L_e)	**58 in.**
Span	**120 in.**
Failure Mode	**Flexure**
Maximum Load	**33.2 kips**
Maximum Moment	**772 kip-in**
Deflection @ Failure	**1.5 in.**
Rebound after complete unloading	**1.4 in.**
Average Transfer Length (L_t) @ release	**16.5 in.**
@ time of testing	**28.0 in.**
Average NASP P.O value for strand 0.5 in.“A”	**20.95 kips**

TEST SUMMARY

Before starting the test it was discovered that the region of concrete below the strands at the North end was damaged and the strands were exposed from under up to about 2.25 in. (East) and 3.75 in (West). Support point was fixed at 11 in. (instead of 4 in.) from the North end. To adjust the symmetry the constant moment region was changed from 24 in. to 27 in. and the total span was kept 120 in.

Damage caused during transportation at the North end (bottom).

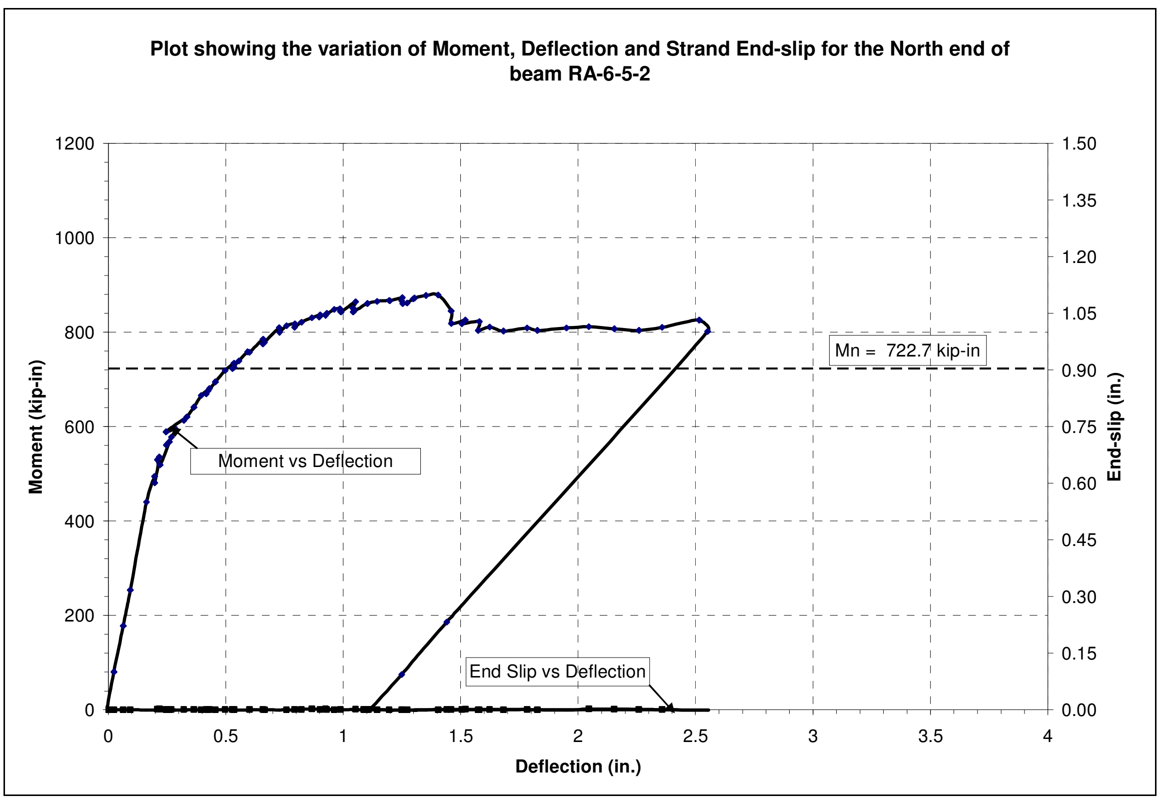
Load was applied in approximately 3 kips increments till first flexural cracking. Beyond this point the deflection was incremented by 0.03 in. till total deflection reached 1.00 in. Further increments of deflection were kept 0.05 in. up to failure.

First flexural crack was observed at 20.0 kips at deflection of 0.1 in. First flexural cracks were formed in two pairs located symmetrically about the two point loads.

Cracking was audible at 29.1 kips (deflection = 0.6 in.). Beyond this load, at all further increments cracking was audible. Concrete crushing was noted at the load of 33.2 kips (deflection 1.4 in.) at the top surface of concrete. Crushing of concrete was violent with considerable spalling of concrete.

Deflection was further incremented up to 2.5 in. After this load was attained, the beam was unloaded completely. End-slip readings at both ends remained 0.000 in. throughout the loading and unloading cycles.

Cracking pattern demonstrated 9 cracks in the middle 50 in. span with average crack spacing = 6.3 in. Width of central crack at maximum deflection (2.5 in.) was 3/8th in. First flexural crack was observed at Stn. 43 from the North end.



Cracking pattern for Beam RA-6-5-2 being loaded at North end

BEAM NAME: RA-6-5-2
END: SOUTH
DATE: 08/05/2005

TEST PARAMETERS	
Concrete Compressive Strength	**8500 psi**
Embedment Length(L_e)	**46 in.**
Span	**120 in.**
Failure Mode	**Flexure**
Maximum Load	**37.0 kips**
Maximum Moment	**777 kip-in**
Deflection @ Failure	**1.5 in.**
Average Transfer Length (L_t) @ release	**15.0 in.**
@ time of testing	**23.5 in.**
Average NASP P.O value for strand 0.5 in.“A”	**20.95 kips**

TEST SUMMARY

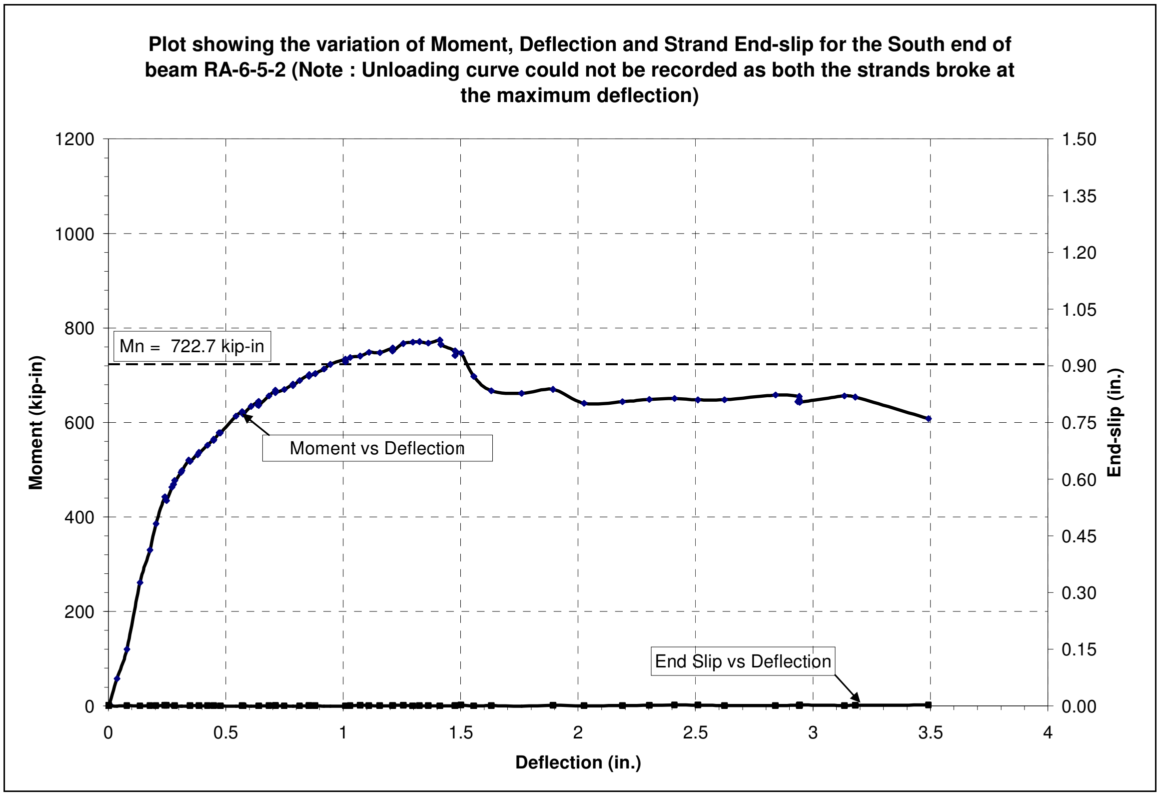
Load was applied in approximately 3.0 kips increments till first flexural cracking. Beyond this point the deflection was incremented by 0.03 in. till total deflection reached 1.00 in. Further increments of deflection were kept 0.05 in. up failure.

First flexural crack was observed at 22.7 kips at deflection of 0.3 in. First flexural cracks were observed in two pairs located symmetrically about the two point loads. Central crack was formed at the net increment (Load = 23.8 kips. deflection = 0.4 in.).

Concrete crushing failure was noticed at the load of 37.0 kips and deflection 1.5 in. Crushed concrete became loose and started falling apart rapidly at the deflection of 1.9 in.

Deflection increments were continued up to strand fracture. Fracture was observed at the deflection of 3.3 in.

Cracking pattern included 9 cracks in middle 59 in span with average crack spacing = 6.6 in. First flexural crack was located at Stn. 37 from the South end.



Cracking pattern for Beam RA-6-5-2 being loaded at South end

BEAM NAME: RA-6A-5-1
END: NORTH
DATE: 08/05/2005

TEST PARAMETERS	
Concrete Compressive Strength	**11420 psi**
Embedment Length(L_e)	**73 in.**
Span	**162 in.**
Failure Mode	**Flexure**
Maximum Load	**22.3 kips**
Maximum Moment	**769 kip-in.**
Deflection @ Failure	**2.4 in.**
Rebound after complete unloading	**2.1 in.**
Average Transfer Length (L_t) @ release	**17.7 in.**
@ time of testing	**26.5 in.**
Average NASP P.O value for strand 0.5 in."A"	**20.95 kips.**

TEST SUMMARY

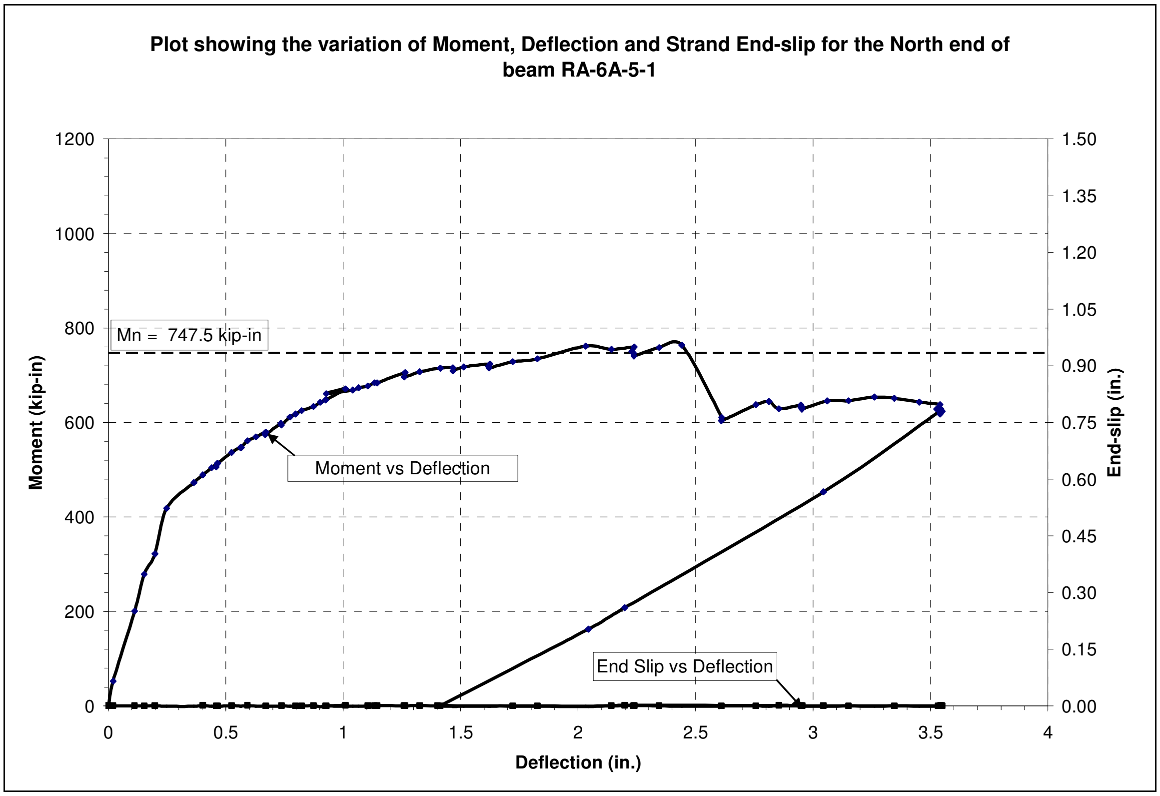
Load was applied in approximately 1.5 kips increments till first flexural cracking. Beyond this point the deflection was incremented by 0.03 in. till total deflection reached 1.00 in. Further increments of deflection were kept 0.05 in. up to 2.0 in. From this point till failure deflection increments were set to 0.1 in.

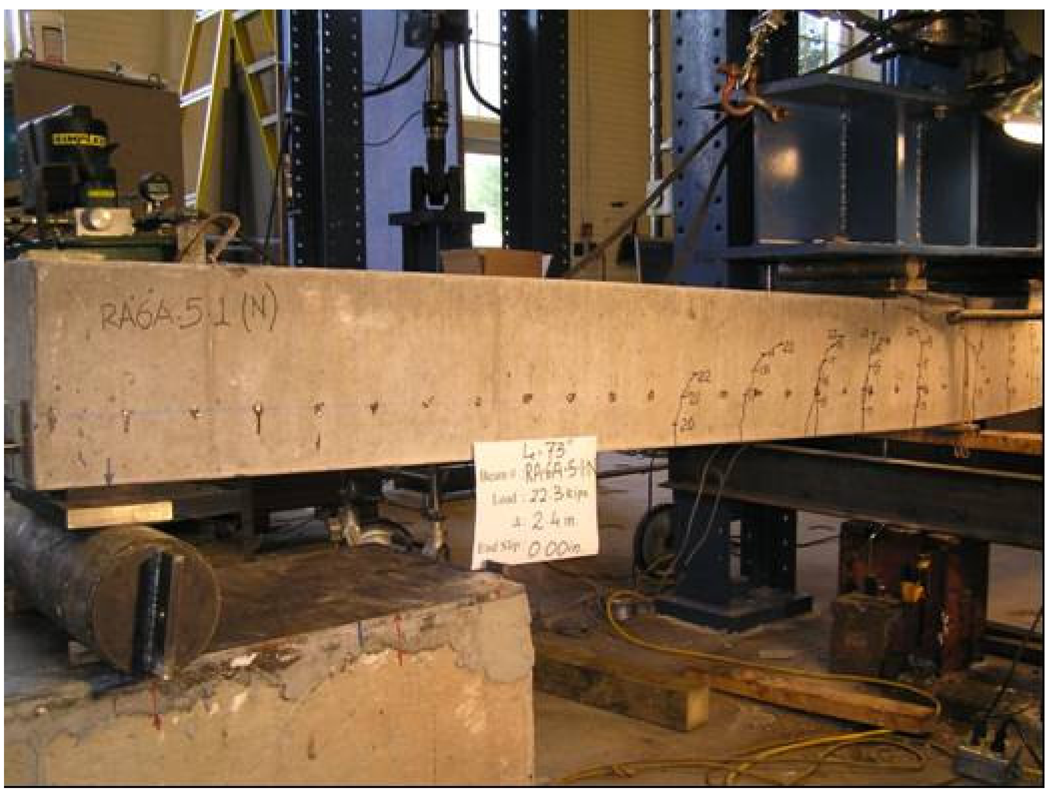
First flexural crack was observed at 12.8 kips at deflection of 0.3 in. First flexural cracks occurred in two pairs located symmetrically about the two point loads.

Cracks in the region between the two point loads started bifurcating near the top surface at the load of 20.2 kips (deflection = 1.2 in.) Audible cracks were observed at 22.1 kips (deflection = 2.3 in.) and finally concrete crushing failure occurred at 22.4 kips (deflection = 2.4 in.)

Deflection increments were continued till the total deflection reached the value of 3.5 in. The beam was completely unloaded after this deflection was attained. End- Slip for loading and unloading cycles remained 0.00 in. at both ends.

The cracking pattern included 11 cracks in the middle 74 in. span. With average crack spacing = 7.4 in. First flexural crack was observed at Stn. 47. from the North end.





Cracking pattern for Beam RA-6A-5-1 being loaded at North end

BEAM NAME: RA-6A-5-1
END: SOUTH
DATE: 08/08/2005

TEST PARAMETERS	
Concrete Compressive Strength	**11420 psi**
Embedment Length(L_e)	**58 in.**
Span	**132 in.**
Failure Mode	**Flexure**
Maximum Load	**28.5 kips**
Maximum Moment	**770 kip-in**
Deflection @ Failure	**1.7 in.**
Rebound after complete unloading	**1.7 in.**
Average Transfer Length (L_t) @ release	**17.7 in.**
@ time of testing	**28.6 in.**
Average NASP P.O value for strand 0.5in."A"	**20.95 kips**

<u>TEST SUMMARY</u>

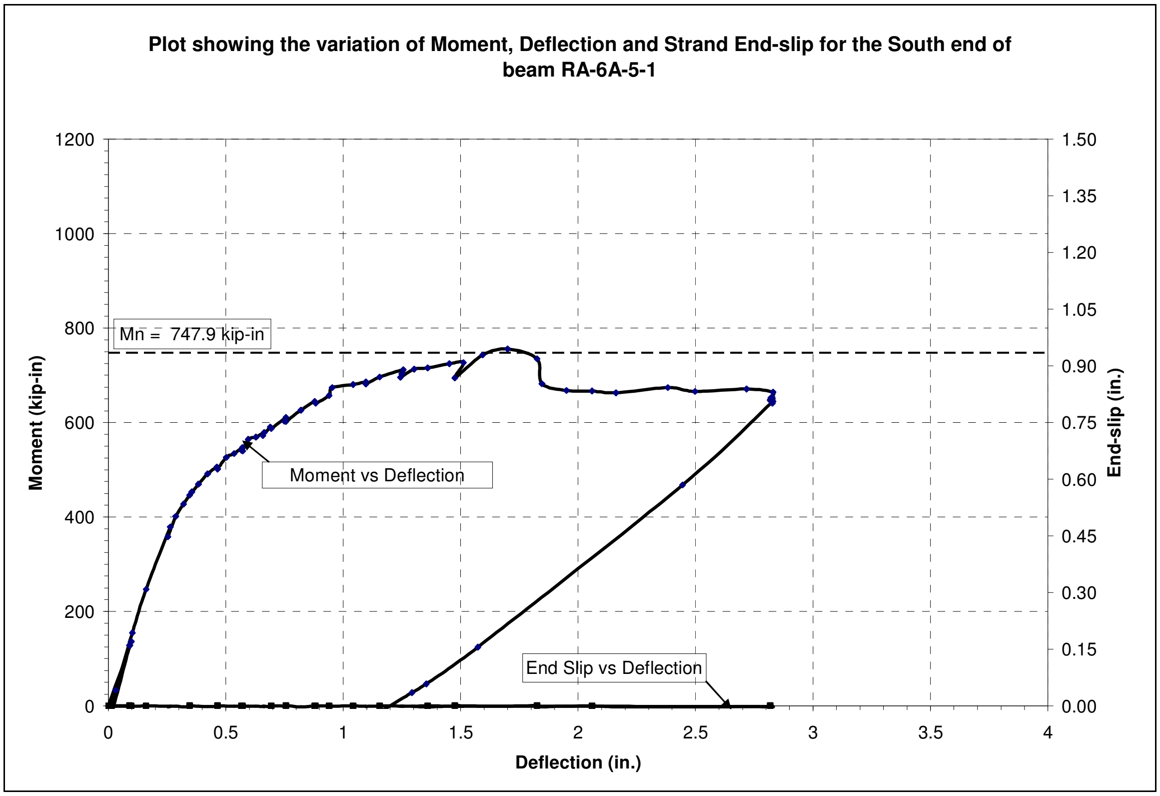
Load was applied in approximately 1.5 kips increments till first flexural cracking. Beyond this point the deflection was incremented by 0.03 in. till total deflection reached 1.00 in. Further increments of deflection were kept 0.05 in. up to failure.

First flexural crack was observed at 18.0 kips at deflection of 0.4 in. First flexural cracks were formed as a pair symmetrically located cracks about the two point loads. The second pair of cracks was observed just at the next increment (load = 18.5 kips. 0.4 in.).

At the load of 28.1 kips (deflection = 1.0 in.) the cracks became clearly audible. Cracking sound became louder at the load of 28.5 kips (deflection = 1.6 in.).

Finally concrete crushing failure was observed at the load of 28.6 kips (deflection = 1.7 in.). The deflection was continued to be incremented up to total deflection of 2.7 in.

Pattern of cracking included 9 cracks in the middle 66 in. span with average crack spacing of 8.25 in. The first flexural crack was located at Stn. 39 from the South end.



Cracking pattern for Beam RA-6A-5-1 being loaded at South end.

BEAM NAME: RA-6A-5-2
END: NORTH
DATE: 08/08/2005

TEST PARAMETERS	
Concrete Compressive Strength	**11420 psi**
Embedment Length(L_e)	**58 in.**
Span	**132 in.**
Failure Mode	**Flexure**
Maximum Load	**29.2 kips**
Maximum Moment	**788 kip-in**
Deflection @ Failure	**1.9 in.**
Rebound after complete unloading	**1.8 in.**
Average Transfer Length (L_t) @ release	**24.5 in.**
@ time of testing	**31.8 in.**
Average NASP P.O value for strand 0.5 in."A"	**20.95 kips**

TEST SUMMARY

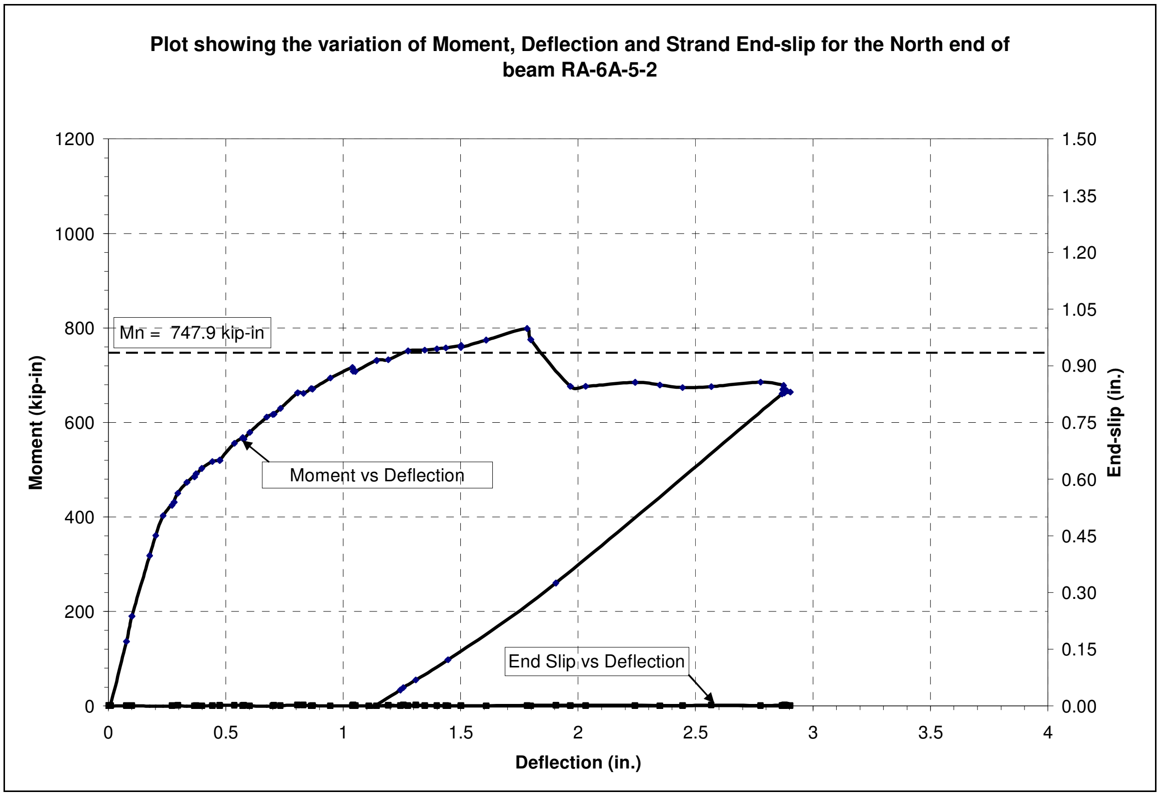
Load was applied in approximately 1.5 kips increments till first flexural cracking. Beyond this point the deflection was incremented by 0.03 in. till total deflection reached 1.00 in. Further increments of deflection were kept 0.05 in. up to failure and beyond failure if was set to 0.1 in.

First flexural crack was observed at 16.5 kips at deflection of 0.3 in.

Cracks became audible at the load of 27.8 kips. (deflection = 1.3 in.). Flexural cracking was heard for a longer time at the load of 29.2 kips. (deflection = 1.8 in.)

Concrete crushing failure was observed at the load of 29.8 kips (deflection = 1.9 in.). Deflection was incremented up to total deflection of 2.8 in.

Cracking pattern included 8 cracks in middle 50 in span. First flexural crack was noted at Stn. 42 from the North end. End-slip at both the ends remained at 0.00 in. No inclined flexural cracks were observed.



Cracking pattern for Beam RA-6A-5-2 being loaded at North end

BEAM NAME: RA-6A-5-2
END: SOUTH
DATE: 08/08/2005

TEST PARAMETERS	
Concrete Compressive Strength	**11420 psi**
Embedment Length(L_e)	**46 in.**
Span	**120 in.**
Failure Mode	**Flexure**
Maximum Load	**37.5 kips**
Maximum Moment	**788 kip-in**
Deflection @ Failure	**1.7 in.**
Rebound after complete unloading	**1.6 in.**
Average Transfer Length (L_t) @ release	**22.0 in.**
@ time of testing	**29.4 in.**
Average NASP P.O value for strand 0.5 in."A"	**20.95 kips**

TEST SUMMARY

Load was applied in approximately 1.5 kips increments till first flexural cracking. Beyond this point the deflection was incremented by 0.03 in. till total deflection reached 1.00 in. Further increments of deflection were kept 0.05 in. up to 2.0 in. From this point deflection increments were set to 0.1 in.

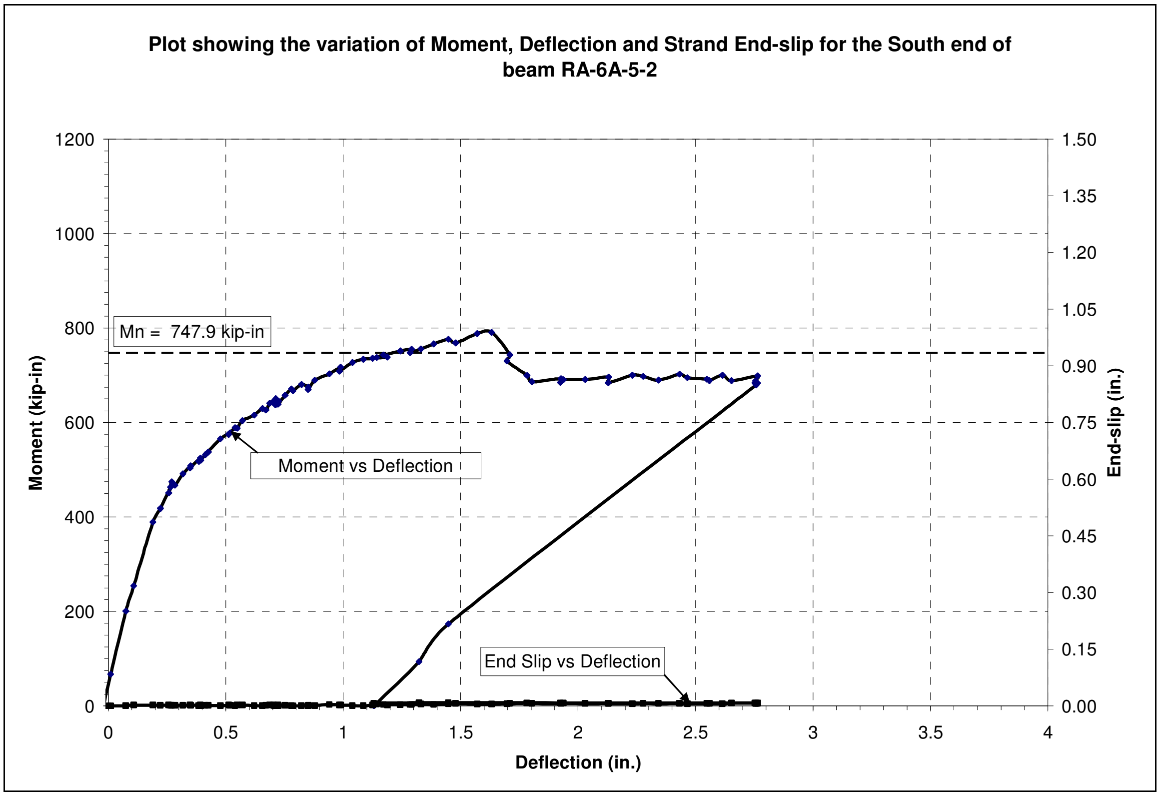
First flexural crack was observed at 20.6 kips at deflection of 0.2 in. Cracks became audible at the load of 29.6 kips (deflection = 0.6 in.)

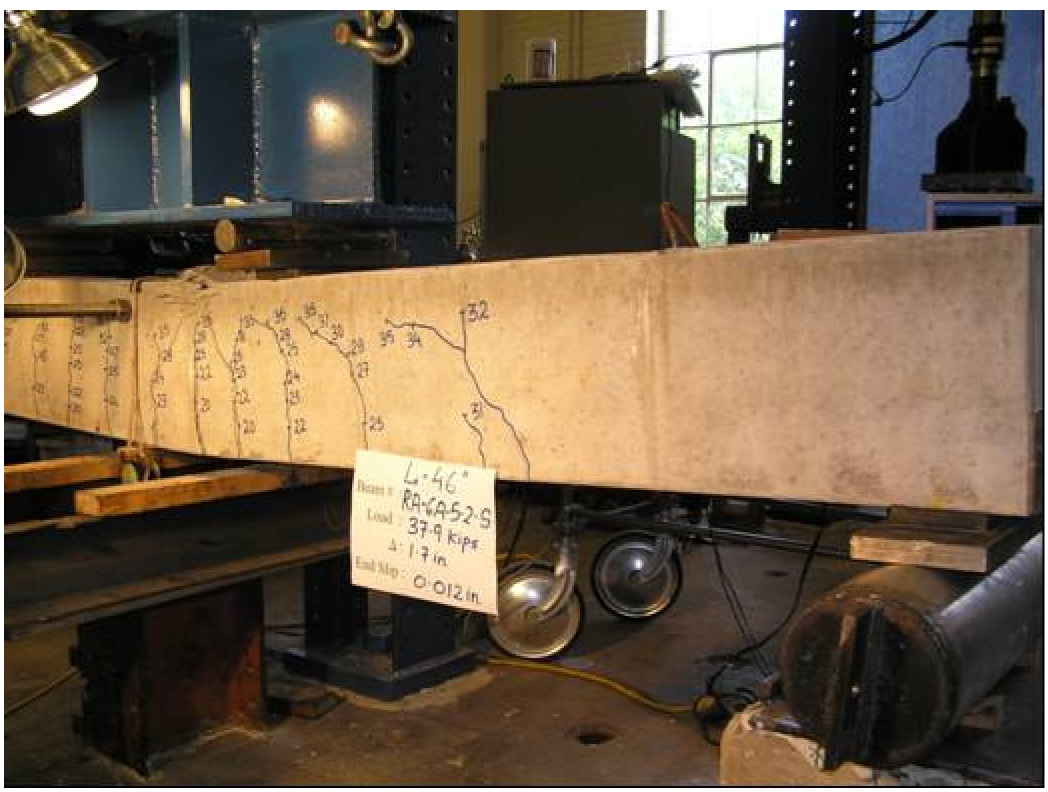
At 33.1 kips. (deflection = 0.9 in.) a sudden inclined flexural crack was noticed at Stn. 26 from the South end.

Concrete crushing failure was observed at 38.1 kips. (deflection = 1.7 in) at the top surface. Concrete started spalling with every further deflection increment. Also it was noticed that only one of the central flexural crack was widening with each increment (final width at the highest deflection of 2.7 in. = 3/8th in.)

Cracking pattern included 11 flexural cracks in the middle 60 in. span. With average crack spacing of 6 in. Inclined flexural crack was observed at Stn. 26 from the South end.

Maximum end-slip = 0.01 in. End-slip at the North end remained 0.000 in.





Cracking pattern for Beam RA-6A-5-2 being loaded at South end.

BEAM NAME: RA-8-5-1
END: NORTH
DATE: 08/09/2005

TEST PARAMETERS	
Concrete Compressive Strength	**13490 psi**
Embedment Length(L_e)	**58 in.**
Span	**132 in.**
Failure Mode	**Flexure**
Maximum Load	**30.7 kips**
Maximum Moment	**829 kip-in**
Deflection @ Failure	**1.7 in.**
Deflection @ strand fracture	**2.6 in.**
Average Transfer Length (L_t) @ release	**13.3 in.**
@ time of testing	**24.9 in.**
Average NASP P.O value for strand 0.5in."A"	**20.95 kips**

TEST SUMMARY

Load was applied in approximately 2.5 kips increments till first flexural cracking. Beyond this point the deflection was incremented by 0.03 in. till total deflection reached 1.00 in. Further increments of deflection were kept 0.05 in. up to 2.0 in. From this point deflection increments were set to 0.1 in.

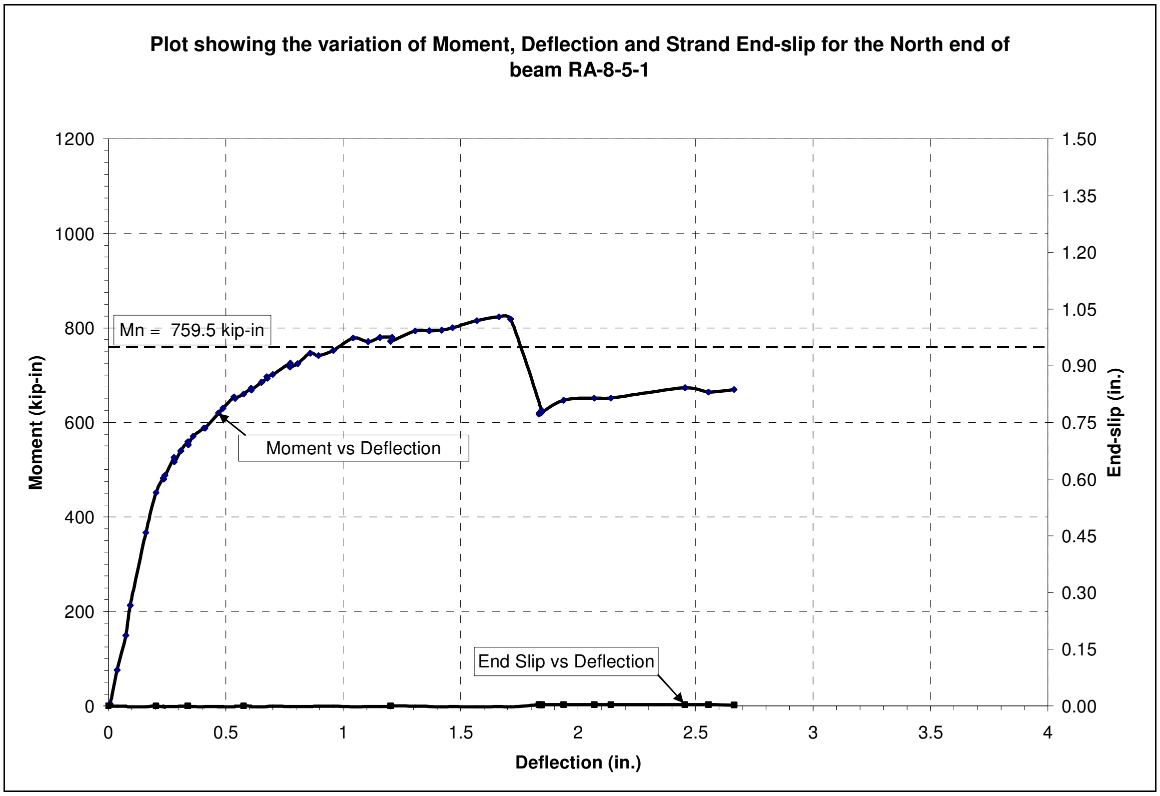
First flexural crack was observed at 18.5 kips at deflection of 0.2 in. Initially three cracks were noted at two point loads and at approximately midpoint of the two load points.

Cracks became audible at the load of 27.0 kips (deflection = 0.8 in.).

At the load of 30.7 kips at deflection of 1.7 in. concrete crushing failure was observed along with the first East strand end-slip of 0.01 in. End-slip of the West strand remained 0.000 in. Also end-slip at the South end remained 0.000 in.

Deflection increments were continued until both the strands fractured at the total deflection of 2.6 in. End-slip of east strand at North end remained 0.01 in. while all other end-slip readings were 0.000 in.

The cracking pattern included 8 flexural cracks in the middle 58 in. span with average crack spacing = 8.3 in. No inclined flexural crack was noticed. First flexural crack was at Stn. 39 from the North end.



Cracking pattern for Beam RA-8-5-1 being loaded at North end

BEAM NAME: RA-8-5-1
END: SOUTH
DATE: 08/10/2005

TEST PARAMETERS	
Concrete Compressive Strength	**13490 psi**
Embedment Length(L_e)	**46 in.**
Span	**120 in.**
Failure Mode	**Flexure**
Maximum Load	**39.6 kips**
Maximum Moment	**832 kip-in**
Deflection @ Failure	**1.9 in.**
Rebound after complete unloading	**1.4 in.**
Average Transfer Length (L_t) @ release	**13.3 in.**
@ time of testing	**24.91 in.**
Average NASP P.O value for strand 0.5 in."A"	**20.95 kips**

TEST SUMMARY

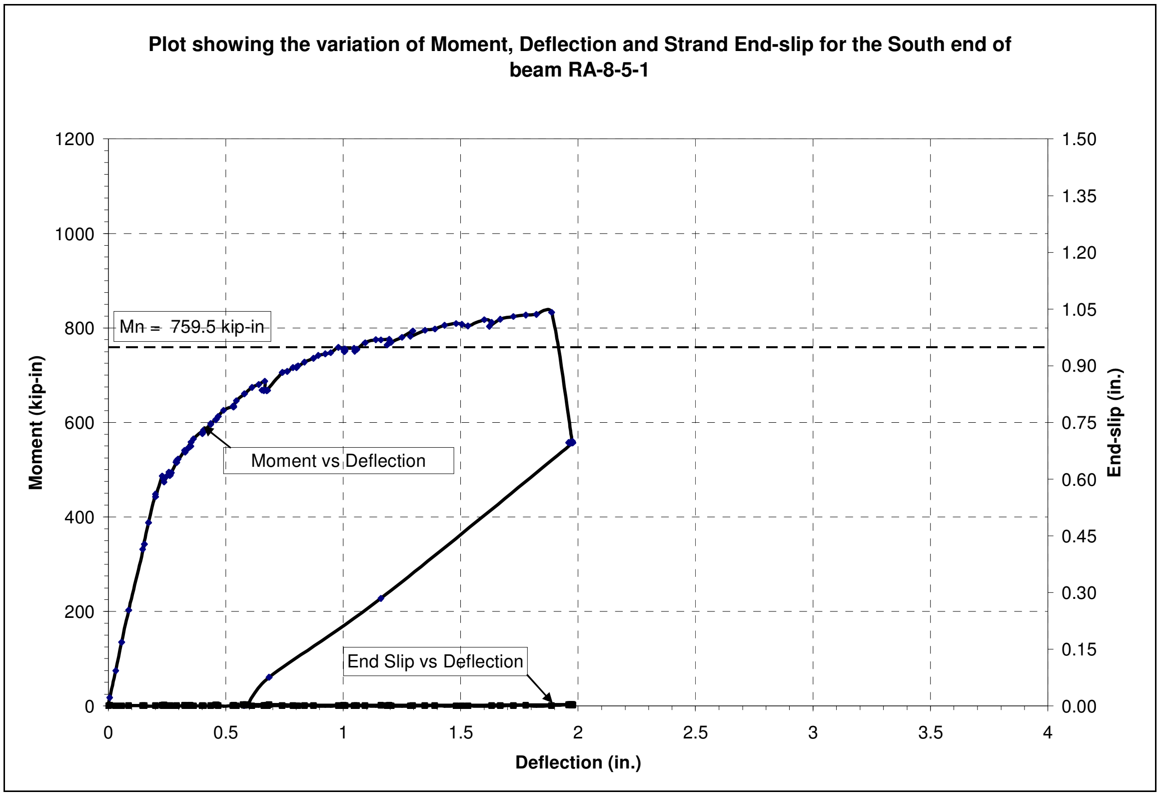
Load was applied in approximately 1.5 kips increments till first flexural cracking. Beyond this point the deflection was incremented by 0.03 in. till total deflection reached 1.00 in. Further increments of deflection were kept 0.05 in. up to 2.0 in. From this point deflection increments were set to 0.1 in.

First flexural crack was observed at 25 kips at deflection of 0.3 in. Initially three cracks were noted, all within the two load points and located symmetrically about the midpoint. At the same load and deflection, a sudden jerk was observed and it was similar to one occurring when end-slip occurs. End-slip reading at the South end remained 0.000 and the reading at the North end could not be recorded as the strands had fractured during the North end testing.

A crack similar to an inclined flexural crack was observed suddenly at 32.3 kips. (deflection = 0.7 in.) at 15 in. from the North support, crossing the originally existing cracks formed during North end testing. (This crack marked with dotted line in the photograph)

Cracking was clearly audible at 37.9 kips (deflection = 1.4 in.) Concrete crushing failure was observed with a bang at 39.6 kips (deflection = 1.9 in.). Concrete at the top surface between the two point supports was completely crushed and fell out as the load reached its peak.

End-slip at the South end remained 0.000 in. throughout the loading cycle. Cracking pattern at the South end shows 9 cracks in the middle 53 in. span with average crack spacing = 6.6 in. No inclined flexural crack was visible at the South side.



Cracking pattern at South end for Beam RA-8-5-1 (South side being tested)

Cracking pattern at the North Support for Beam RA-8-5-1 (South side being tested)

BEAM NAME: RA-10-5-1
END: NORTH
DATE: 08/10/2005

TEST PARAMETERS	
Concrete Compressive Strength	**14470 psi**
Embedment Length(L_e)	**58 in.**
Span	**132 in.**
Failure Mode	**Flexure**
Maximum Load	**29.2 kips**
Maximum Moment	**788 kip-in**
Deflection @ Failure	**1.7 in.**
Rebound after complete unloading	**1.5 in.**
Average Transfer Length (L_t) @ release	**24.3 in.**
@ time of testing	**24.3 in.**
Average NASP P.O value for strand 0.5 in."A"	**20.95 kips**

TEST SUMMARY

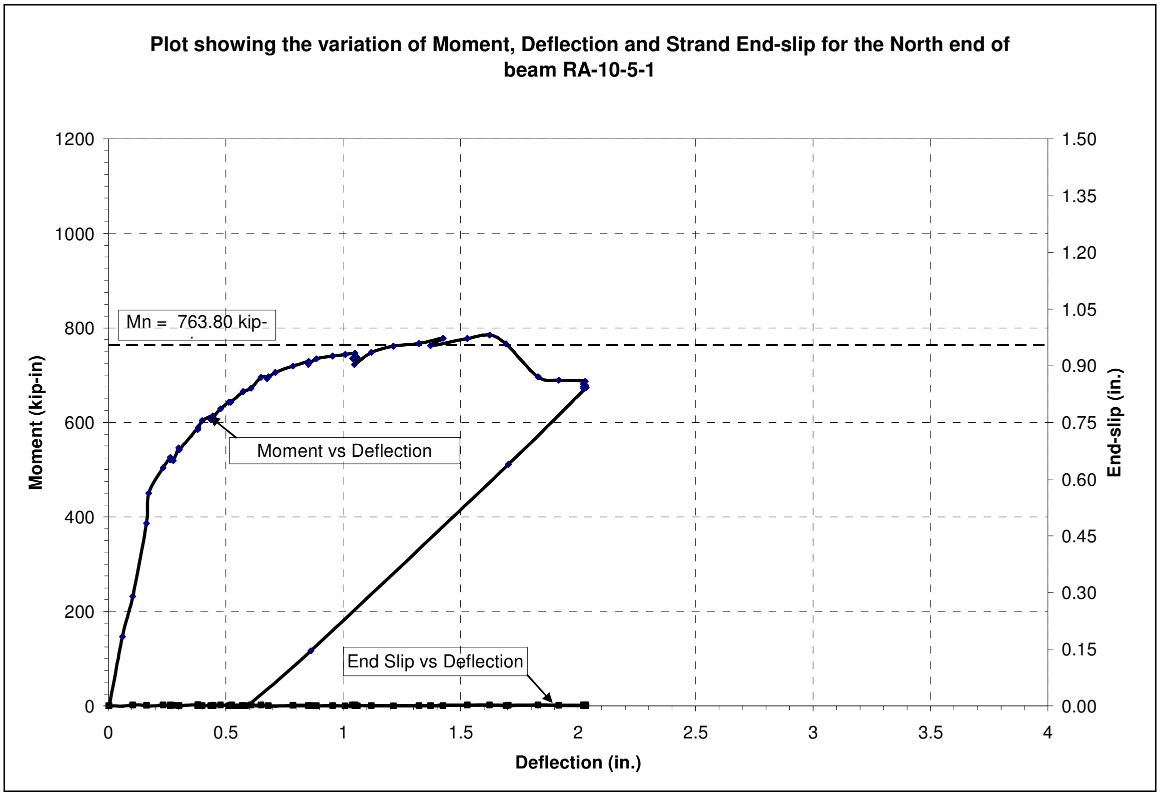
Load was applied in approximately 2.5 kips increments till first flexural cracking. Beyond this point the deflection was incremented by 0.03 in. till total deflection reached 1.00 in. Further increments of deflection were kept 0.05 in. up to 2.0 in. deflection increments were set to 0.1 in.

First flexural crack was observed at 19.3 kips at deflection of 0.2 in. First flexural crcks were formed as two pairs symmetrically located about the midpoint.

No significant changes were noticed till the load reached 29.1 kips (deflection = 1.6 in.). At this point the cracks were clearly audible. Concrete crushing failure was noticed at 29.2 kips. (deflection = 1.7 in.)

Cracking pattern shows 9 cracks in the middle 56 in. with average crack spacing of 7 in. The first flexural crack was at Stn. 43. No inclined flexural crack was visible.

End-slip at both ends remained 0.000 in. throughout the loading and unloading cycles.



Cracking pattern for Beam RA-10-5-1 being loaded at North end

BEAM NAME: RA-10-5-1
END: SOUTH
DATE: 08/10/2005

TEST PARAMETERS	
Concrete Compressive Strength	**14470 psi**
Embedment Length(L_e)	**46 in.**
Span	**120 in.**
Failure Mode	**Flexure**
Maximum Load	**37.9 kips**
Maximum Moment	**796 kip-in**
Deflection @ Failure	**1.7 in.**
Rebound after complete unloading	**1.5 in.**
Average Transfer Length (L_t) @ release	**9.69 in.**
@ time of testing	**13.14 in.**
Average NASP P.O value for strand 0.5 in."A"	**20.95 kips**

TEST SUMMARY

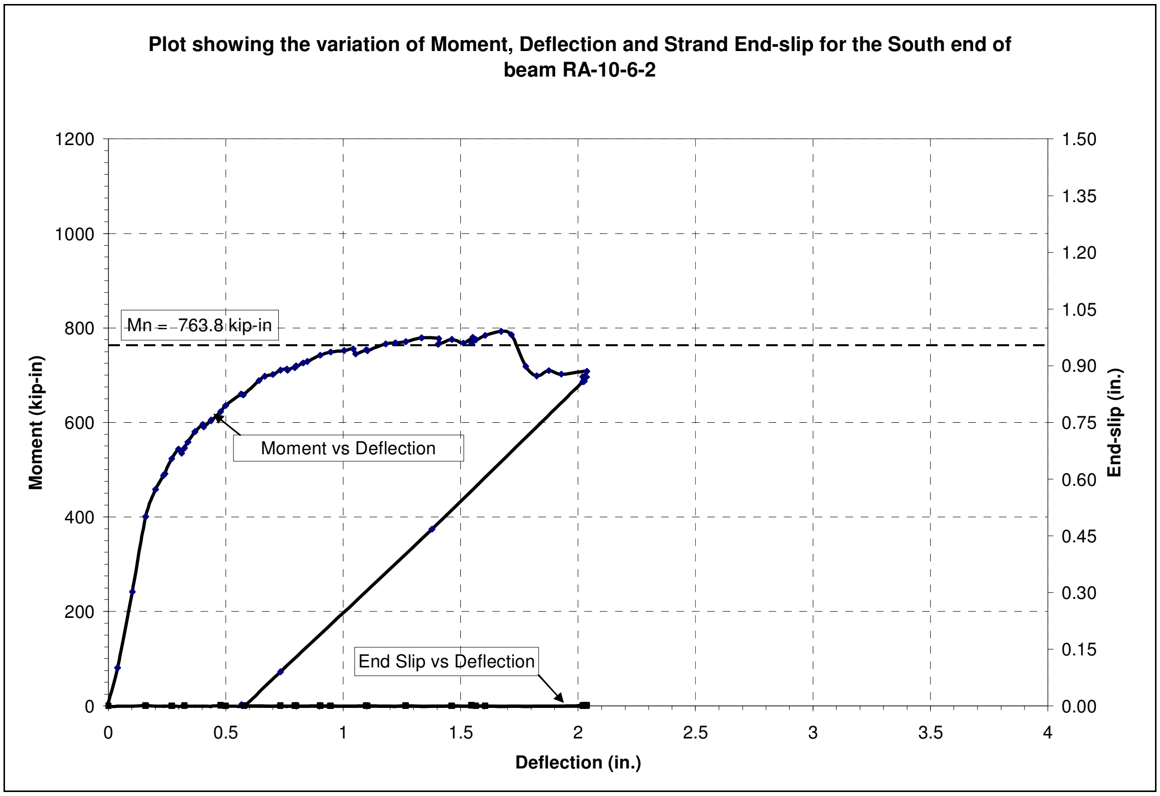
Load was applied in approximately 3.5 kips increments till first flexural cracking. Beyond this point the deflection was incremented by 0.03 in. till total deflection reached 1.00 in. Further increments of deflection were kept 0.05 in. up to 2.0 in. From this point deflection increments were set to 0.1 in.

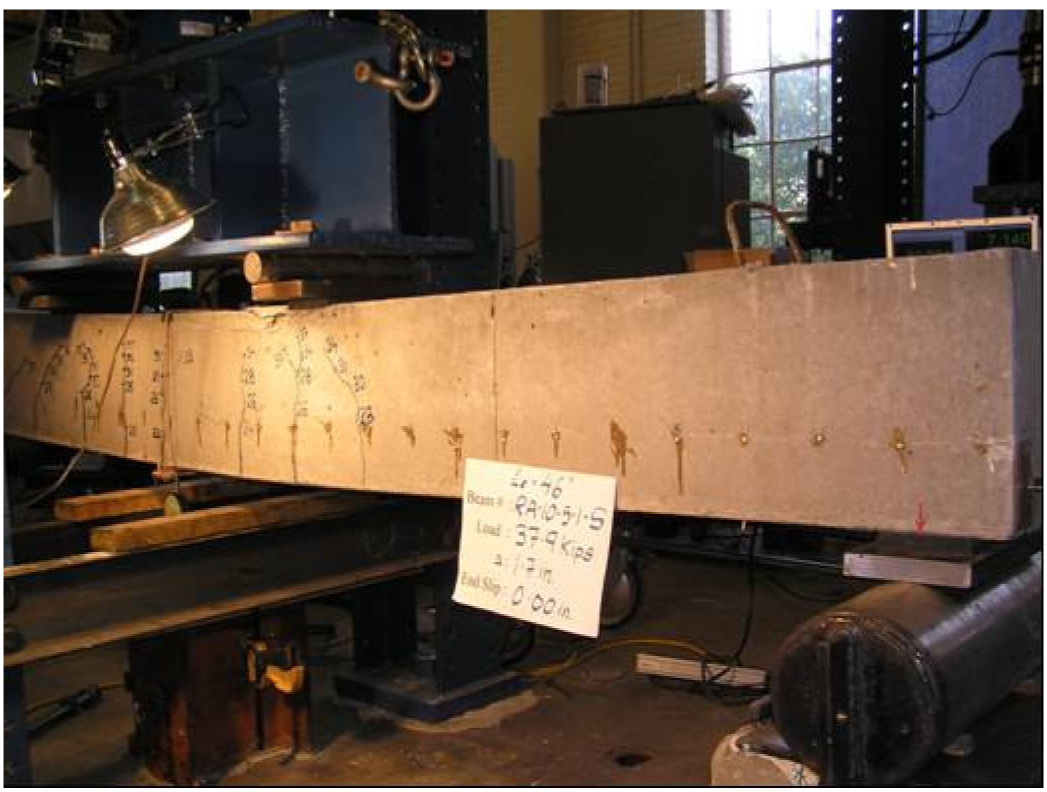
First flexural crack was observed at 24 kips at deflection of 0.2 in. Initially three cracks were noted in between the two point loads located symmetrically about the midpoint.

Cracks became clearly audible at 34.3 kips (deflection = 0.8 in.) Concrete crushing failure was observed at 37.8 kips (deflection = 1.7 in.) Deflection was further incremented till the total deflection reached 2.0 in.

Cracking pattern included 8 cracks in the middle 55 in. span with average crack spacing of 7.9 in. First flexural crack was located at Stn. 41. No inclined flexural crack was visible.

End-slip at both the ends remained 0.000 in throughout the loading an unloading cycles.





Cracking pattern for Beam RA-10-5-1 being loaded at South end

BEAM NAME: RB-4-5-1
END: NORTH
DATE: 07/20/2005

TEST PARAMETERS	
Concrete Compressive Strength	**7050 psi**
Embedment Length(L_e)	**73 in.**
Span	**162 in.**
Failure Mode	**Flexure**
Maximum Load	**22.5 kips**
Maximum Moment	**776 kip-in**
Deflection @ Failure	**1.9 in.**
Rebound after complete unloading	**1.6 in.**
Average Transfer Length (L_t) @ release	**18.4 in.**
@ time of testing	**22.1 in.**
Average NASP P.O value for strand "B"	**20.21 kips**

TEST SUMMARY

Load was applied in approximately 2.5 kips increments till first flexural cracking. Beyond this point the deflection was incremented by 0.03 in. till total deflection reached 1.00 in. Further increments of deflection were kept 0.05 in. up to failure.

First flexural cracking was discovered at a load of 16.8 kips while deflection at this point was noted as 0.5 in. The first flexural cracks formed at three locations, one of which was exactly under the point load whereas the other two were approximately equal distance from the central crack. With gradual loading these cracks propagated upward and diagonally towards the top rollers which were acting as two point loads.

At the load of approx 20 kips (deflection 1.0 in.) fourth crack was observed while the first three cracks grew gradually in width and length.

Peak load attained was 22.5 kips(deflection 1.9 in.) at which concrete crushing failure occurred with audible sound. Concrete spalling was clearly observed at the top surface.

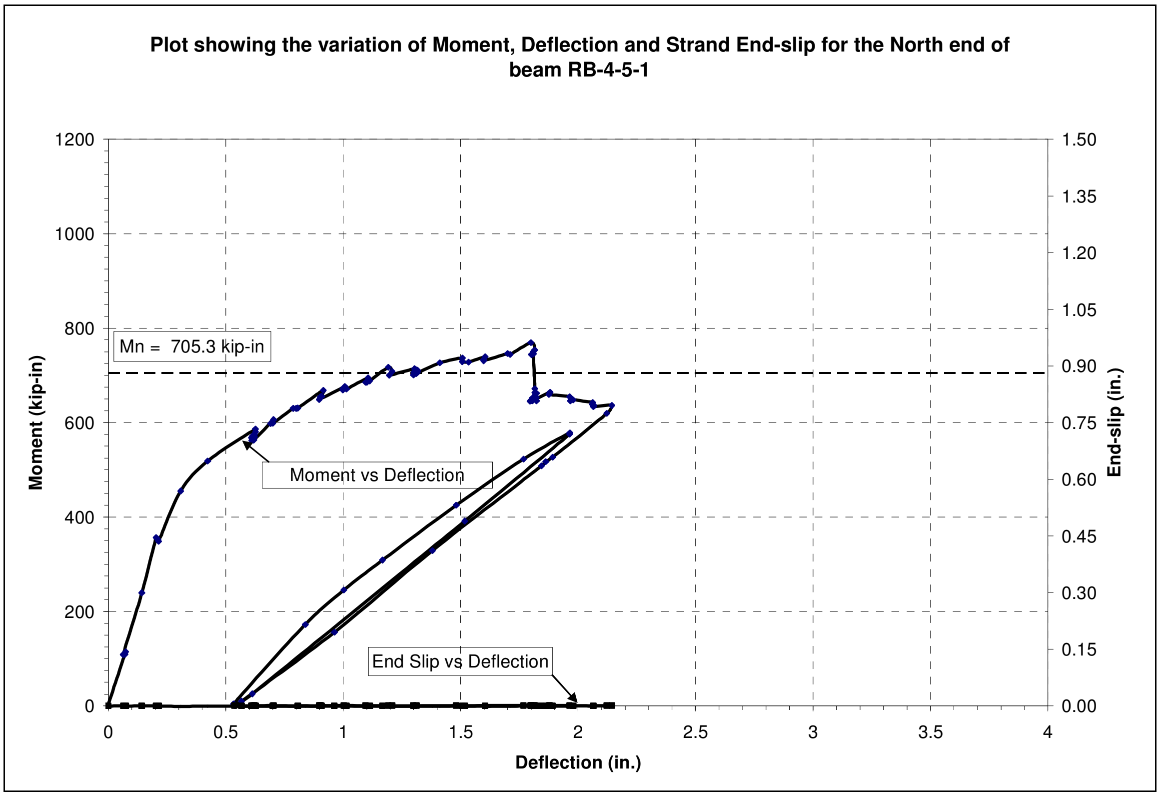
Since crack growth was clearly audible, loading was paused for 5 minutes to allow complete cracking under the same load.

As loading was started again, the beam failed to give enough reaction and the load started to reduce in magnitude. Hence it was decided to stop further loading as deflection was increasing while load being decreased.

Since this was the first beam to be tested, the beam was reloaded for observation. At this loading cycle, greater deflection was noted for comparatively smaller loads than the first cycle. Finally the beam was completely unloaded and readings for end slips and deflection were noted at zero load.

Throughout the loading cycles, the end slips remained at zero indicating strong bond between concrete and the strand so as to allow the beam to gain its complete flexural strength.

Cracking pattern included 11 flexural cracks in the middle 70 in. span with average crack spacing = 7 in. No inclined flexural crack was observed.



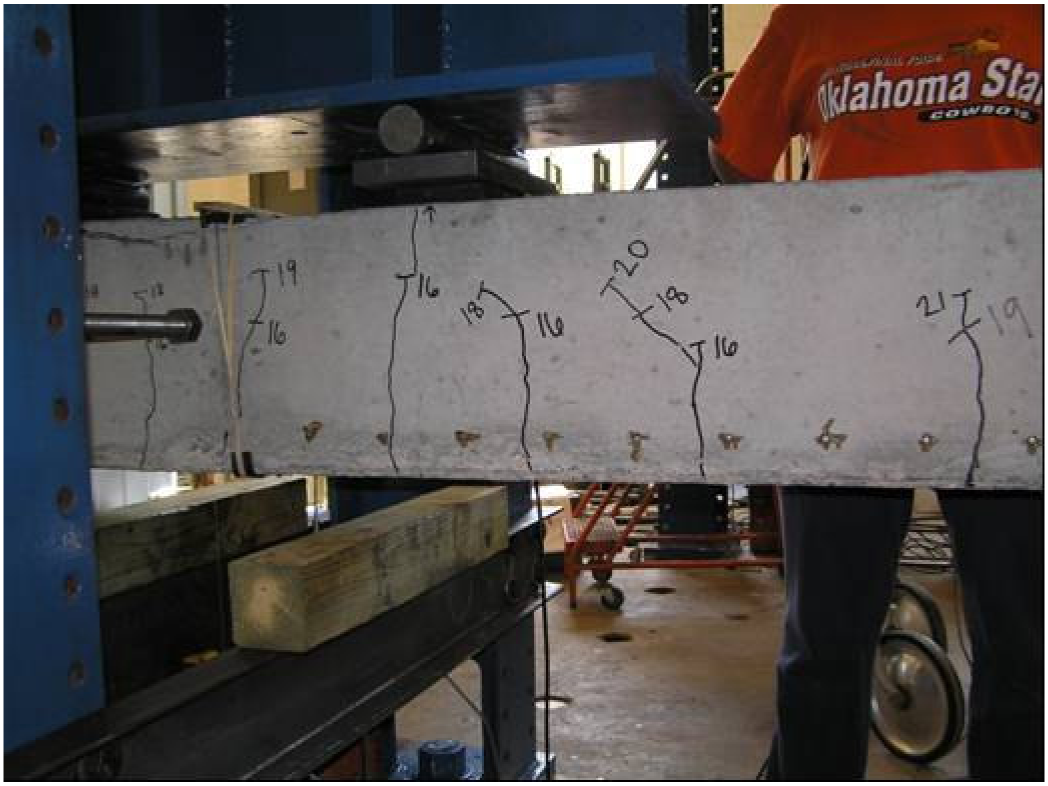


Photo Showing cracking pattern for Beam RB-4-5-1 being loaded at North end

BEAM NAME: RB-4-5-1
END: SOUTH
DATE: 07/20/2005

TEST PARAMETERS	
Concrete Compressive Strength	**7050 psi**
Embedment Length(L_e)	**58 in.**
Span	**132 in.**
Failure Mode	**Flexure**
Maximum Load	**29.7 kips**
Maximum Moment	**980 kip-in**
Deflection @ Failure	**2.0 in.**
Rebound after complete unloading	**1.6 in.**
Average Transfer Length (L_t) @ release	**18.5 in.**
@ time of testing	**20.5 in.**
Average NASP P.O value for strand "B"	**20.21 kips**

TEST SUMMARY

Load was applied in approximately 2.5 kips increments till first flexural cracking. Beyond this point the deflection was incremented by 0.03 in. till total deflection reached 1.00 in. Further increments of deflection were kept 0.05 in. up to failure.

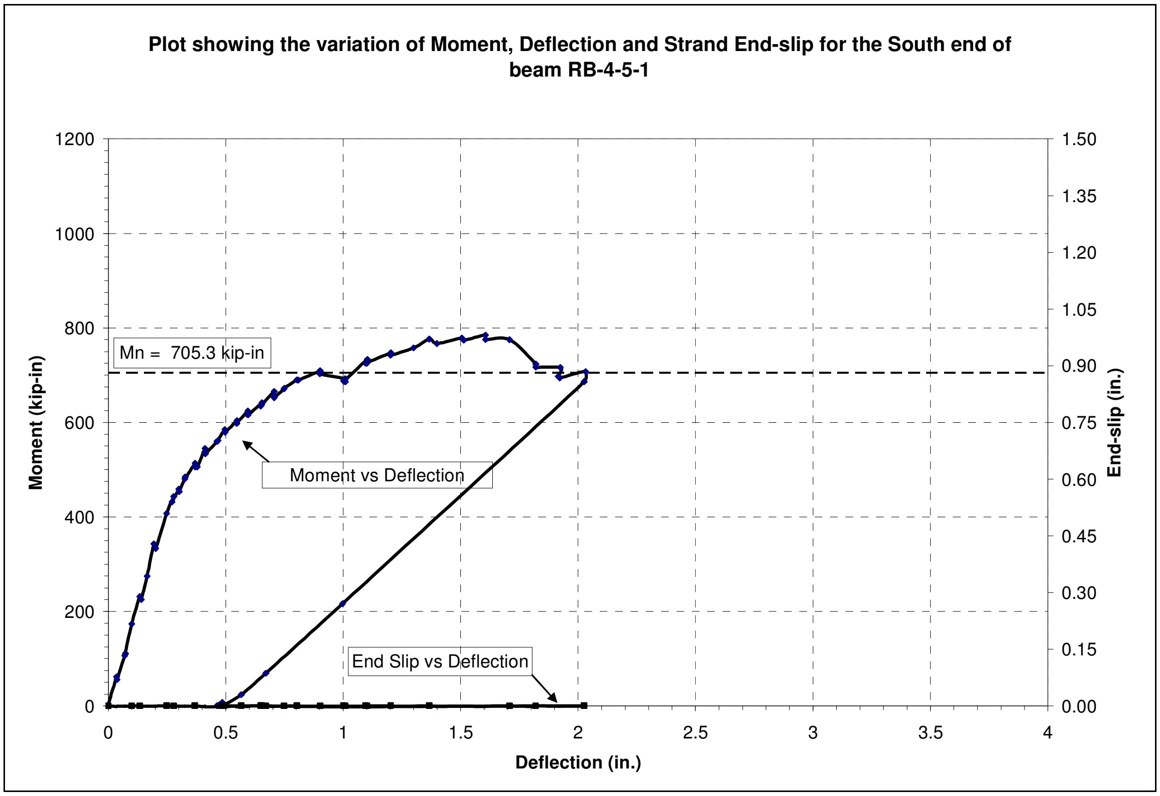
First flexural cracking occurred at a load of 18.6 kips while deflection at this point was noted as 0.4 in. The first flexural cracks formed at three spots, one of which was exactly under the point load whereas the other two were approximately equal distance from the central crack. With gradual loading these cracks propagated upward and diagonally towards the top rollers which were acting as two point loads.

At the load of approx. 23.5 kips (0.6 in. deflection) cracks originated from the already existing cracks due to North end testing and in reverse direction than the original cracks. Further loading up to 26.1 kips (deflection = 0.9 in.) produced audible cracks.

No noticeable changes were observed as the load increased from 26.1 to 29.7 kips. At peak load (29.7 kips) concrete crushing failure occurred with no recordable end slip. At this stage the deflection was noted as 2.0 in.

Load was reduced to zero and the deflection and end slips were again recorded at zero load. End slip reading stayed at zero for entire length of loading and unloading.

Cracking pattern shows 9 cracks in the middle 69 in. span with average crack spacing = 8.6 in. No inclined flexural crack was observed.



Cracking pattern for Beam RB-4-5-1 being loaded at South end

BEAM NAME: RB-4-5-2
END: NORTH
DATE: 07/22/2005

TEST PARAMETERS	
Concrete Compressive Strength	**7050 psi**
Embedment Length(L_e)	**73 in.**
Span	**162 in.**
Failure Mode	**Flexure**
Maximum Load	**20.9 kips**
Maximum Moment	**721 kip-in**
Deflection @ Failure	**2.5 in.**
Rebound after complete unloading	**1.9 in.**
Average Transfer Length (L_t) @ release	**21.1 in.**
@ time of testing	**22.5 in.**
Average NASP P.O value for strand "B"	**20.21 kips**

TEST SUMMARY

Load was applied in approximately 2.5 kips increments till first flexural cracking. Beyond this point the deflection was incremented by 0.03 in. till total deflection reached 1.00 in. Further increments of deflection were kept 0.05 in. till deflection of 2.0 in. Increments were set to 0.1 in. from this point up to failure.

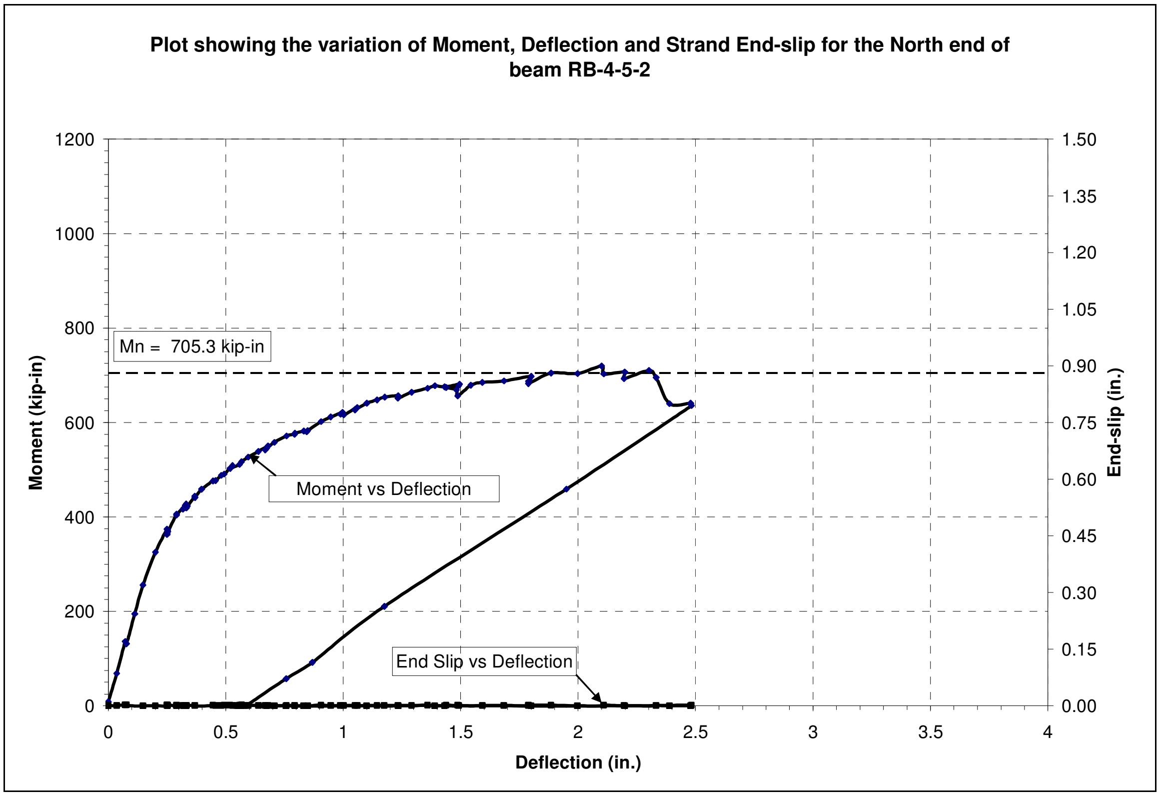
First flexural cracking occurred at a load of 10.6 kips while deflection at this point was noted as 0.3 in. The first flexural cracks formed at three spots, one of which was exactly under the point load whereas the other two were approximately equal distance from the central crack. With gradual loading these cracks propagated upward and diagonally towards the top rollers which were acting as two point loads.

At the load of approx 14.5 kips (deflection 0.5 in.) a pair of cracks was observed approximately symmetric about the point loads and beyond the first three cracks.

Peak load attained was 20.9 kips (deflection 2.49 in.) at which concrete crushing failure occurred with audible sound. Concrete spalling was clearly observed at the top surface.

Throughout the loading cycles, the end slips remained at zero indicating strong bond between concrete and the strand so as to allow the beam to gain its complete flexural strength.

Pattern of cracks displayed 10 cracks in the middle 68 in span with average crack spacing = 7.6 in. No inclined flexural crack was observed.



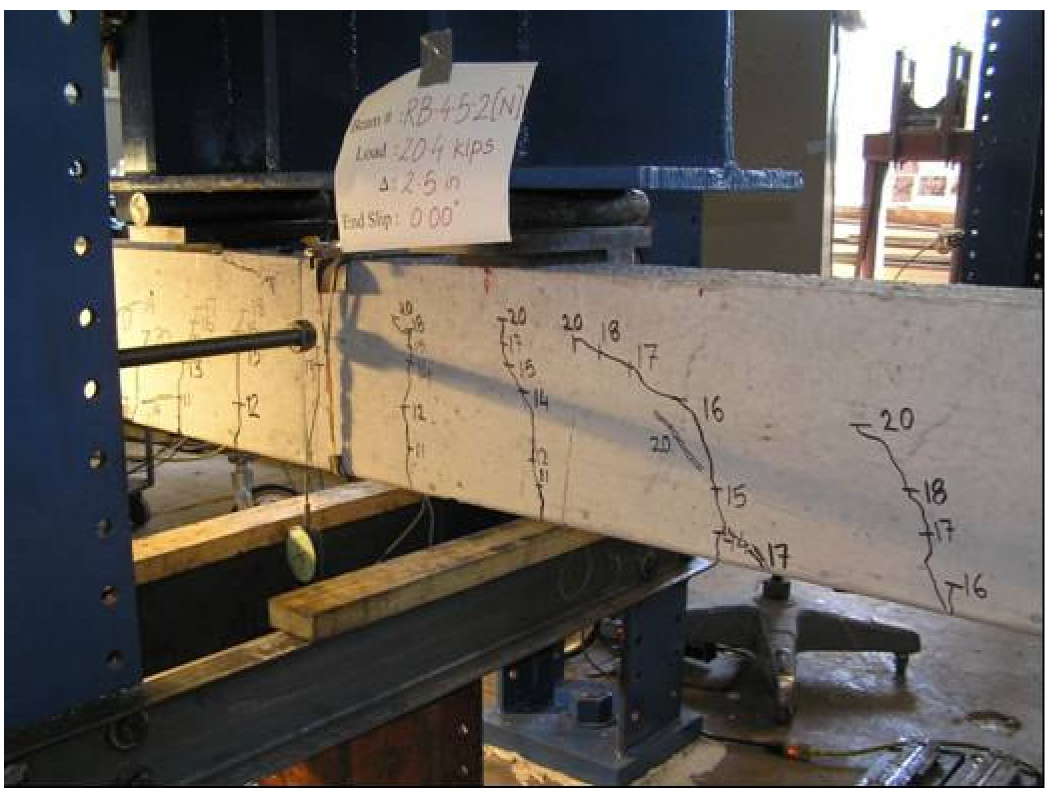


Photo showing cracking pattern for Beam RB-4-5-2 being loaded at North end

BEAM NAME: RB-4-5-2
END: SOUTH
DATE: 07/22/2005

TEST PARAMETERS	
Concrete Compressive Strength	**7050 psi**
Embedment Length(L_e)	**58 in.**
Span	**132 in.**
Failure Mode	**Flexure**
Maximum Load	**27.7 kips**
Maximum Moment	**748 kip-in**
Deflection @ Failure	**2.2 in.**
Rebound after complete unloading	**1.7 in.**
Average Transfer Length (L_t) @ release	**22.5 in.**
@ time of testing	**23.8 in.**
Average NASP P.O value for strand "B"	**20.21 kips**

TEST SUMMARY

Load was applied in approximately 2 kips increments till first flexural cracking. Beyond this point the deflection was incremented by 0.03 in. till total deflection reached 1.00 in. Further increments of deflection were kept 0.05 in. till deflection of 2.0 in. Increments were set to 0.1 in. from this point up to failure.

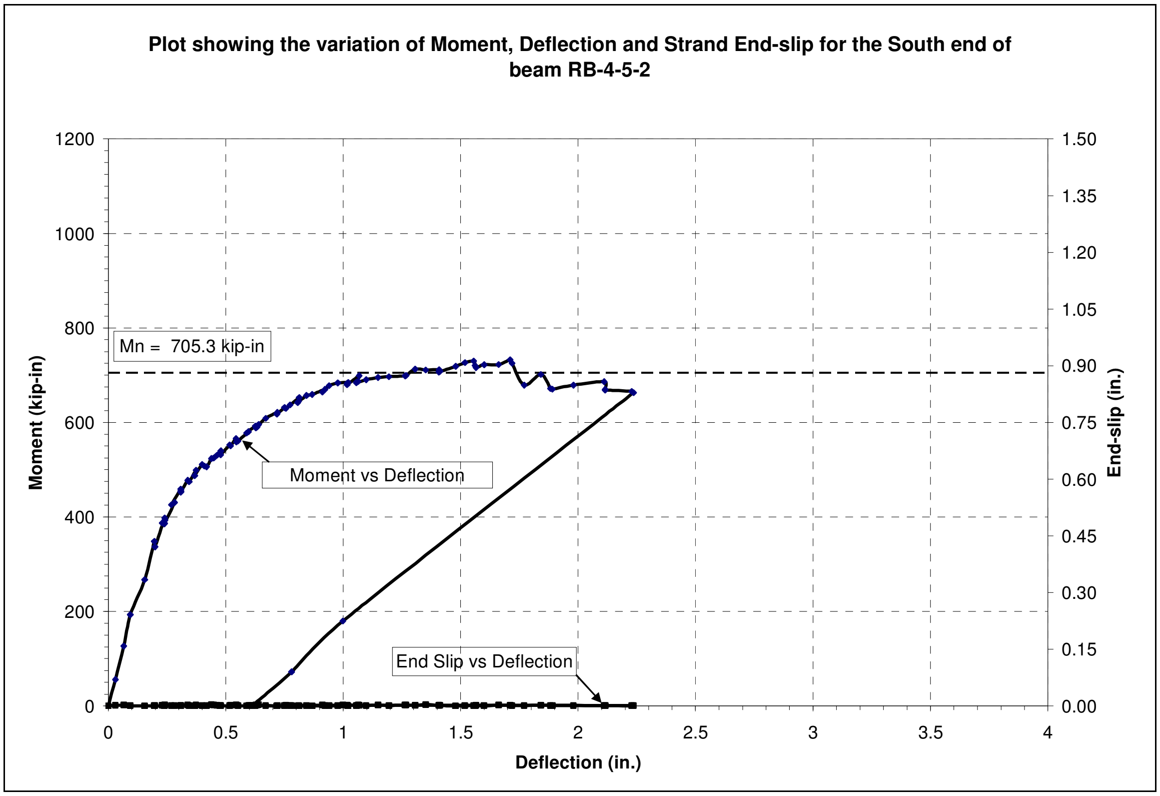
First flexural cracking occurred at a load of 14.7kips while deflection at this point was noted as 0.2 in. The first flexural cracks formed at three spots, one of which was exactly under the point load whereas the other two were approximately equal distance from the central crack. With gradual loading these cracks propagated upward and diagonally towards the top rollers which were acting as two point loads.

Except for widening of cracks, no other noticeable changes were observed as the load increased up to 24.8 kips (deflection 0.9 in.) The cracks could be clearly heard at this point.

Peak load attained was 27.7 kips, at this load concrete crushing failure was noticed with deflection noted as 2.2 in.

Load was reduced to zero and the deflection and end slips were again recorded at zero load. End slip reading stayed at zero for entire length of loading and unloading.

There were 7 cracks noticed in the middle 45 in. span with average crack spacing of 7.5 in. No inclined flexural crack w observed.



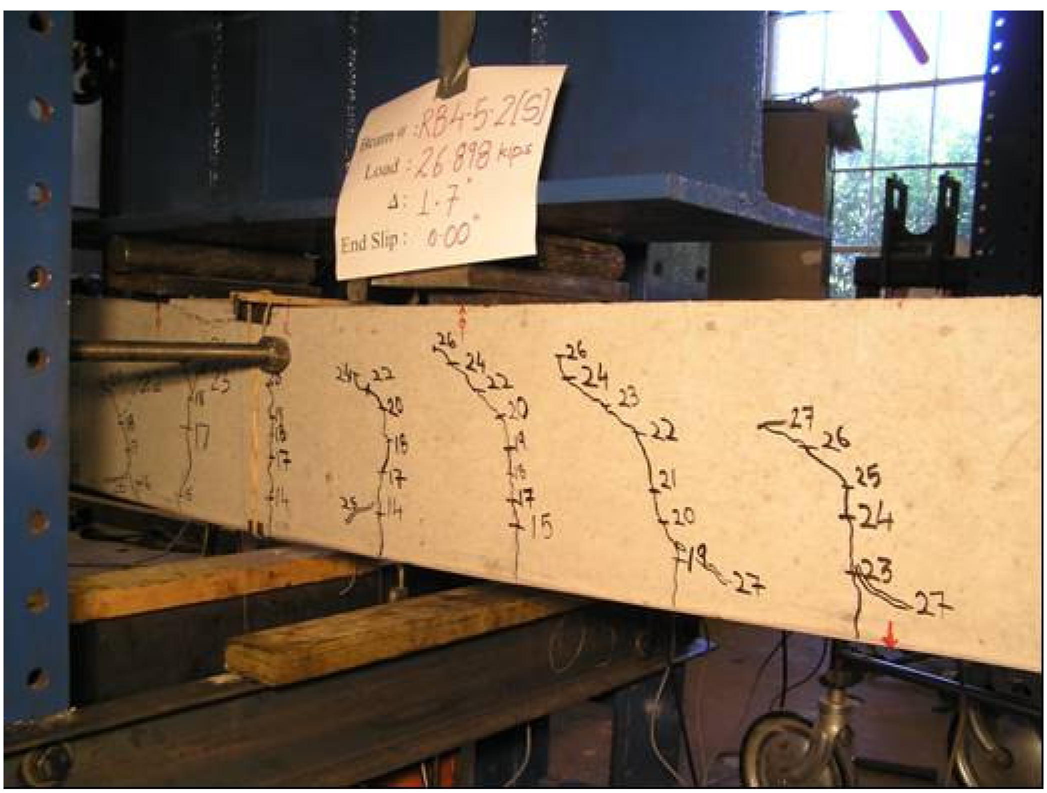


Photo Showing cracking pattern for Beam RB-4-5-2 being loaded at South end

APPENDIX C

DEVELOPMENT LENGTH TEST SUMMARIES FOR RECTANGULAR BEAMS WITH STRAND A (0.6 IN.)

BEAM NAME: RA-4-6-1
END: NORTH
DATE: 08/12/2005

TEST PARAMETERS	
Concrete Compressive Strength	**7050 psi**
Embedment Length(L_e)	**88 in.**
Span	**192 in.**
Failure Mode	**Flexure**
Maximum Load	**25.8 kips**
Maximum Moment	**1084 kip-in**
Deflection @ Failure	**3.0 in.**
Rebound after complete unloading	**2.6 in.**
Average Transfer Length (L_t) @ release	**33.4 in.**
@ time of testing	**41.8 in.**
Average NASP P.O value for strand 0.6 in. "A"	**18.29 kips**

<u>TEST SUMMARY</u>

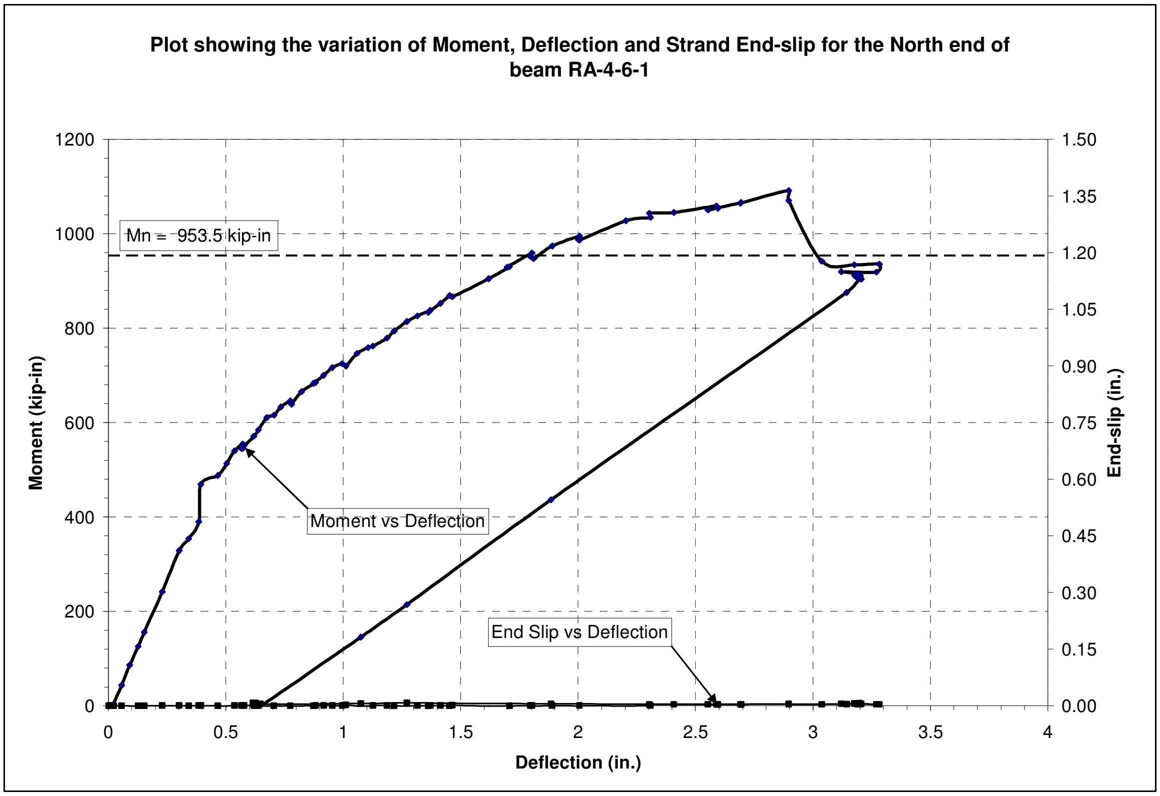
Load was applied in approximately 1.0 kips increments till first flexural cracking. Beyond this point the deflection was incremented by 0.03 in. till total deflection reached 1.00 in. Further increments of deflection were kept 0.05 in. up to 2.0 in. From this point till failure deflection increments were set to 0.1 in.

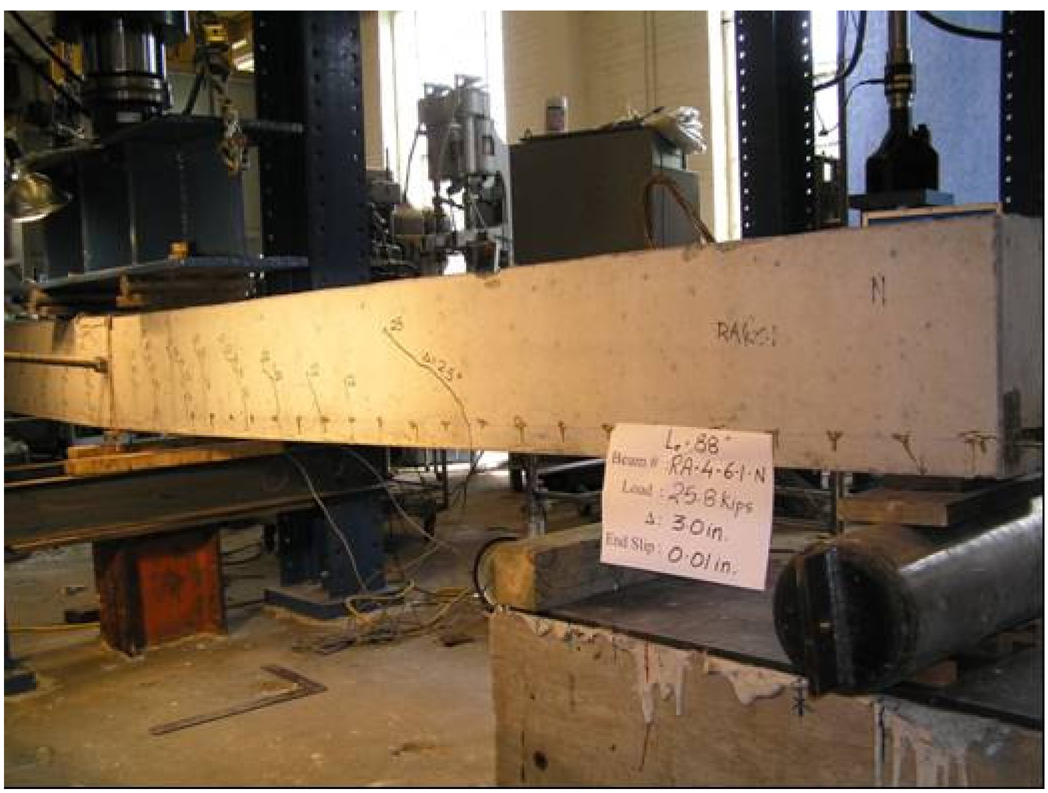
First flexural crack was observed at 13.4 kips at deflection of 0.5 in. First flexural cracking occurred as five cracks symmetrically located about the midpoint.

At 21.1 kips (deflection = 1.5 in.) cracks were audible. At 25.4 kips (deflection = 2.5 in.) a sudden inclined flexural cracks was observed at Stn. 38. Also at this load and deflection first end slip of 0.005 in. was noted.

Concrete crushing failure occurred at the load of 25.8 kips (deflection = 3.0 in.). End-slip at failure was 0.01 in. at the North end. End-slip at the South end remained 0.00 in.

Cracking pattern included 15 cracks in the middle 90 in. span with average crack spacing of 6.4 in. Distance between the first flexural crack and the inclined flexural crack was 15 in.


Plot showing the variation of Moment, Deflection and Strand End-slip for the North end of beam RA-4-6-1
Mn = 953.5 kip-in
Moment vs Deflection
End Slip vs Deflection
Moment (kip-in)
End-slip (in.)
Deflection (in.)
0
200
400
600
800
1000
1200
0.00
0.15
0.30
0.45
0.60
0.75
0.90
1.05
1.20
1.35
1.50
0
0.5
1
1.5
2
2.5
3
3.5
4


L: 88"
Beam # RA-4-6-1-N
Load : 25.8 kips
Δ: 3.0 in.
End Slip : 0.01 in.

Cracking pattern for Beam RA-4-6-1 being loaded at North end

BEAM NAME: RA-4-6-1

END: SOUTH

DATE: 08/12/2005

TEST PARAMETERS	
Concrete Compressive Strength	**7050 psi**
Embedment Length(L_e)	**70 in.**
Span	**156 in.**
Failure Mode	**Flexure**
Maximum Load	**29.2 kips**
Maximum Moment	**964 kip-in**
Deflection @ Failure	**2.7 in.**
Rebound after complete unloading	**1.8 in.**
Average Transfer Length (L_t) @ release	**23.5 in.**
@ time of testing	**28.9 in.**
Average NASP P.O value for strand 0.6 in.“A”	**18.29 kips**

TEST SUMMARY

Load was applied in approximately 1.5 kips increments till first flexural cracking. Beyond this point the deflection was incremented by 0.03 in. till total deflection reached 1.00 in. Further increments of deflection were kept 0.05 in. up to 2.0 in. From this point till failure deflection increments were set to 0.1 in.

Since the embedment lengths were 88 in. for the North end and 70 in. for the South end, a portion of the loading region overlapped for the North and South end testing. As a result flexural cracks already existed below the loading region for the South end test. First flexural crack could not be recorded at particular loads as the pre-existing cracks grew in width instead of formation of new cracks. At 22.0 kips (deflection = 1.3 in.) first new crack was observed towards the South side of the beam.

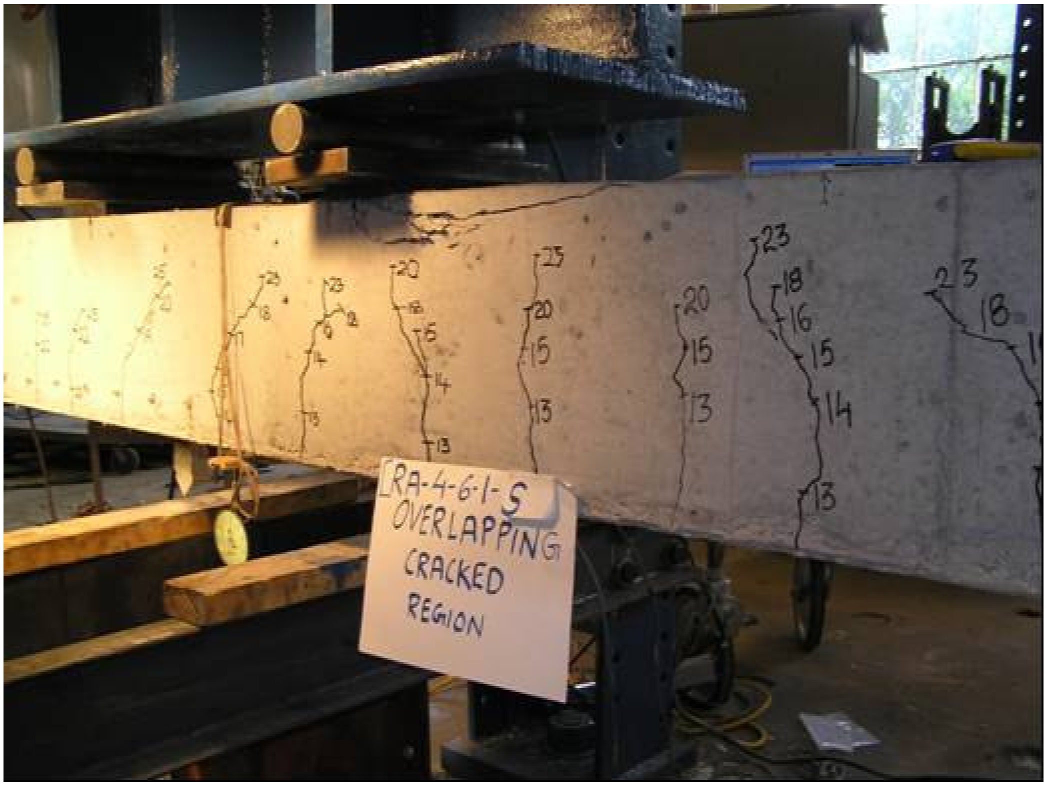


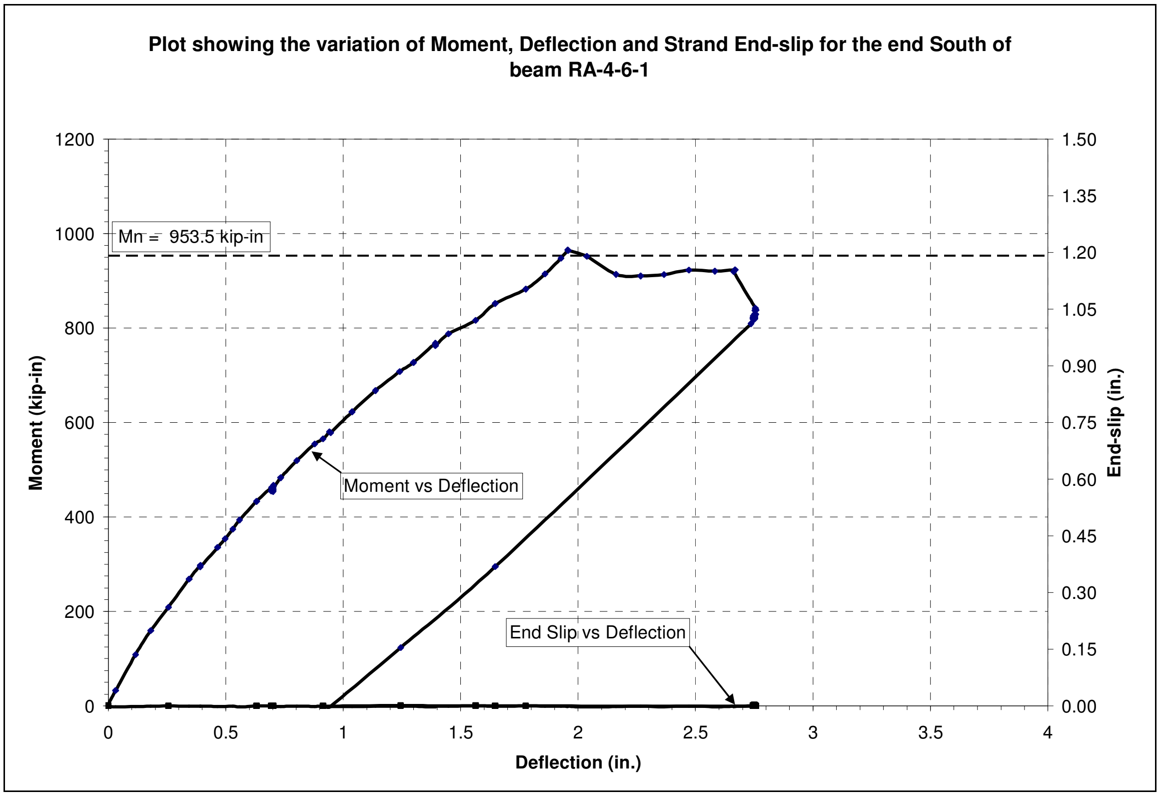
Photo taken before starting the loading cycle for the South end.

With further increments of loads, concrete started spalling from the crushed zone (formed during North end testing).

At 29.2 kips (deflection = 2.7 in.) a sudden jerk was noticed and on observation of the east strand it was evident that one of the strand wires had broken.

As the moment at this point was almost (99.89%) of M_n, the failure was declared to be flexural failure.

No inclined flexural crack was noticed. Cracking pattern included flexural cracks with average spacing of 6.8 in. End slip remained 0.00 at both ends throughout the loading and unloading cycle.



Cracking pattern for Beam RA-6-5-1 being loaded at South end

BEAM NAME: RA-4-6-2
END: NORTH
DATE: 08/15/2005

TEST PARAMETERS	
Concrete Compressive Strength	**7050 psi**
Embedment Length(L_e)	**73 in.**
Span	**162 in.**
Failure Mode	**Flexure**
Maximum Load	**29.3 kips**
Maximum Moment	**1011 kip-in**
Deflection @ Failure	**2.4 in.**
Rebound after complete unloading	**1.9 in.**
Average Transfer Length (L_t) @ release	**30.2 in.**
@ time of testing	**37.7 in.**
Average NASP P.O value for strand 0.6 in. "A"	**18.29 kips**

TEST SUMMARY

Load was applied in approximately 1.5 kips increments till first flexural cracking. Beyond this point the deflection was incremented by 0.03 in. till total deflection reached 1.00 in. Further increments of deflection were kept 0.05 in. up to 2.0 in. From this point till failure deflection increments were set to 0.1 in.

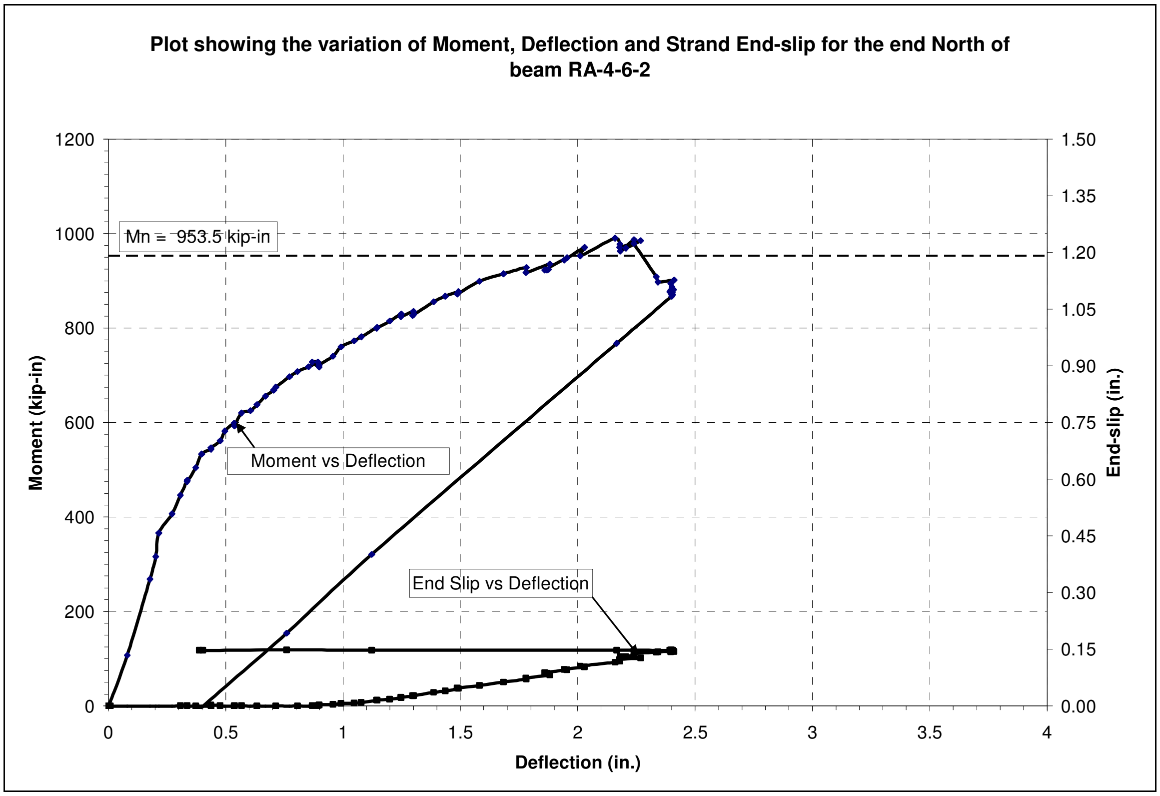
First flexural crack was observed at 14.2 kips at deflection of 0.3 in. First flexural cracks were formed in a pair located symmetrically about the midpoint.

At the load of 21.8 kips (deflection = 0.9 in.) a sudden inclined flexural crack was observed at Stn. 40, along with the first end-slip of 0.007 in. End slip at the other end remains 0.000 in.

Cracks became audible at 24.2 kips (deflection = 1.3 in.) and the inclined flexural crack was observed to widen with increasing increments.

Concrete crushing failure was observed at 29.4 kips (deflection = 2.4 in.) with loud cracking sound.

Cracking pattern includes 11 cracks within the middle 62 in. span with average crack spacing of 6.2 in. The inclined flexural crack originated at Stn. 40 and it bifurcated to touch the bottom surface at Stn. 36. Distance of the first flexural crack and the inclined flexural crack was 17 in. Width of the inclined flexural crack at the deflection of 2.6 in was 1/4th in.



Cracking pattern for Beam RA-4-6-2 being loaded at North end

BEAM NAME: RA-4-6-2
END: SOUTH
DATE: 08/15/2005

TEST PARAMETERS	
Concrete Compressive Strength	**7050 psi**
Embedment Length(L_e)	**58 in.**
Span	**148 in.**
Failure Mode	**Bond**
Maximum Load	**34.1 kips**
Maximum Moment	**921 kip-in**
Rebound after complete unloading	**2.0 in.**
Average Transfer Length (L_t) @ release	**29.3 in.**
@ time of testing	**33.2 in.**
Average NASP P.O value for strand 0.6 in. "A"	**18.29 kips**

TEST SUMMARY

Load was applied in approximately 1.5 kips increments till first flexural cracking. Beyond this point the deflection was incremented by 0.03 in. till total deflection reached 1.00 in. Further increments of deflection were kept 0.05 in. up to 2.0 in. From this point deflection increments were set to 0.1 in.

First flexural crack was observed at 18.8 kips at deflection of 0.4 in.

At 31.2 kips (deflection = 1.4 in.) first end-slip of 0.01 in. was noticed. End-slip at the North end remained 0.000 in.

As the load reached 33.4 kips (deflection = 1.7 in.) concrete which was already crushed during the North end testing suddenly gave jerk and fell out. This previously crushed zone was outside the constant moment region for the South end testing. Load decreased to 32 kips and gradually increased with further increments. At 34.1 kips (deflection = 2.0 in.) concrete outside the constant moment region towards the South side showed a few cracks.

The first flexural crack had a few more cracks moving outwards in diagonal directions giving it an appearance as of an inclined flexural crack. This crack was formed at 45 in. At deflection of 3.0 in. the width of this crack was ½ in. No concrete crushing failure was observed in the constant moment region.

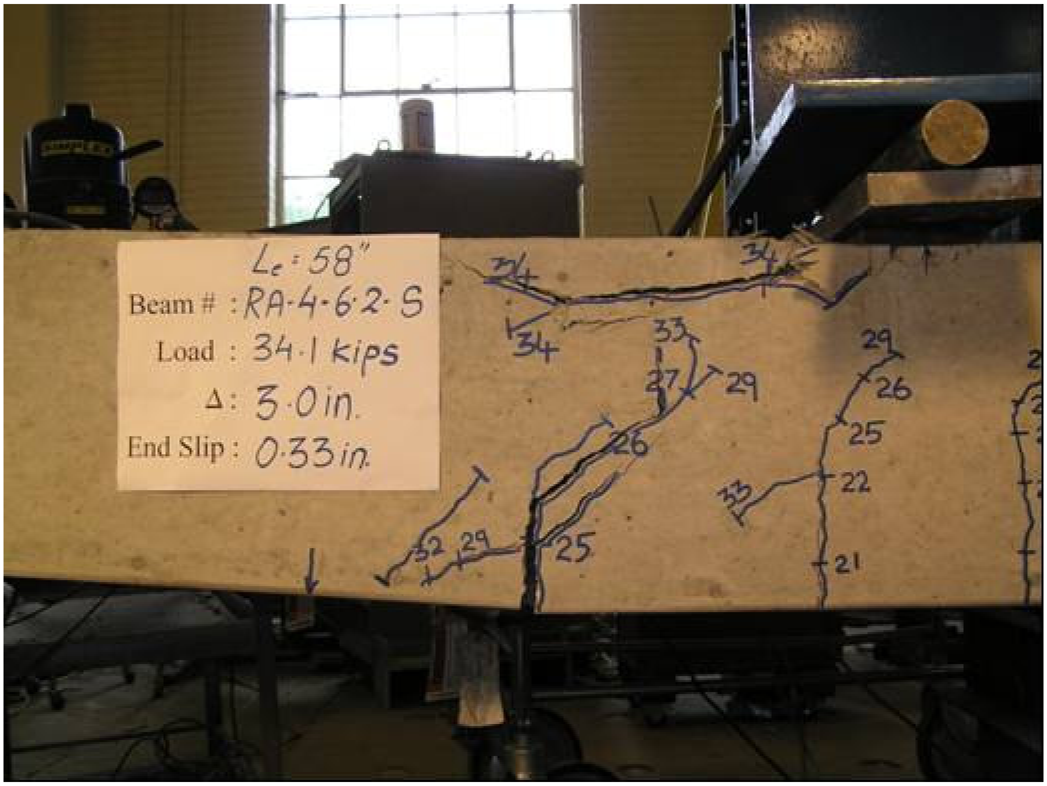
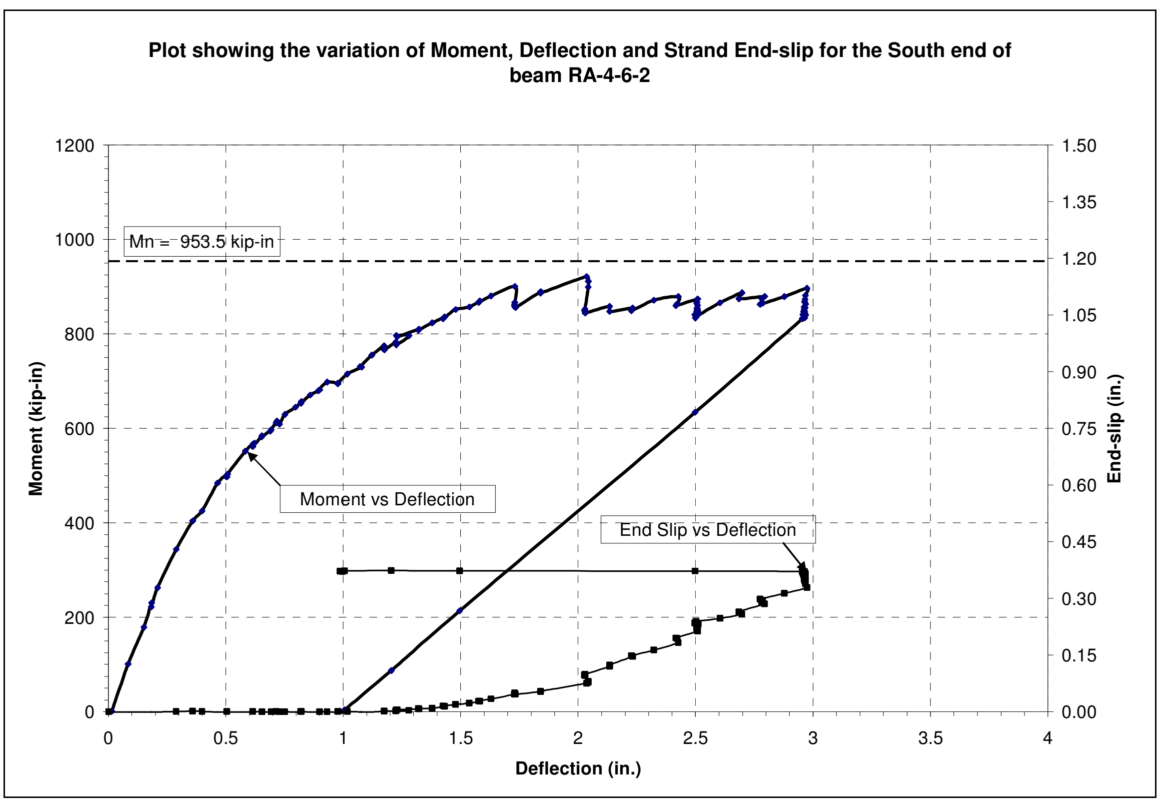


Photo showing the first flexural crack later developed as an inclined flexural crack.



Cracking pattern for Bea m RA-4-6-2 being loaded at South end

BEAM NAME: RA-6-6-1
END: NORTH
DATE: 08/18/2005

TEST PARAMETERS	
Concrete Compressive Strength	**8040 psi**
Embedment Length(L_e)	**88 in.**
Span	**192 in.**
Failure Mode	**Flexure**
Maximum Load	**24.1 kips**
Maximum Moment	**1012.2 kip-in**
Deflection @ Failure	**2.5 in.**
Maximum deflection attained	**5.5 in.**
Rebound after complete unloading	**3.0 in.**
Average Transfer Length (L_t) @ release	**29.7 in.**
@ time of testing	**40.9 in.**
Average NASP P.O value for strand 0.6 in."A"	**18.29 kips**

TEST SUMMARY

Load was applied in approximately 1.5 kips increments till first flexural cracking. Beyond this point the deflection was incremented by 0.03 in. till total deflection reached 1.00 in. Further increments of deflection were kept 0.05 in. up to 2.0 in. From this point deflection increments were set to 0.1 in.

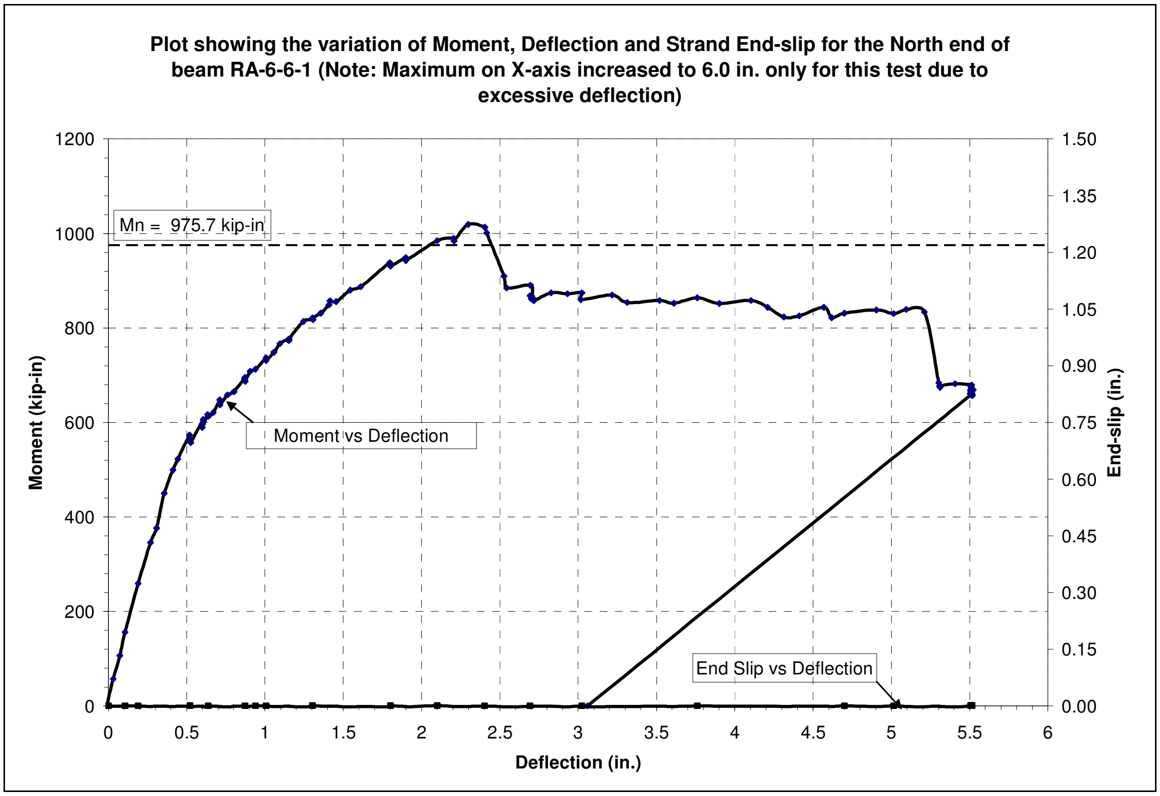
First flexural crack was observed at 13.7 kips at deflection of 0.5 in. First flexural cracks were formed as two pairs of cracks located symmetrically about the midpoint.

Cracks became audible at the load of 23.1kips at the deflection of 2.0 in.

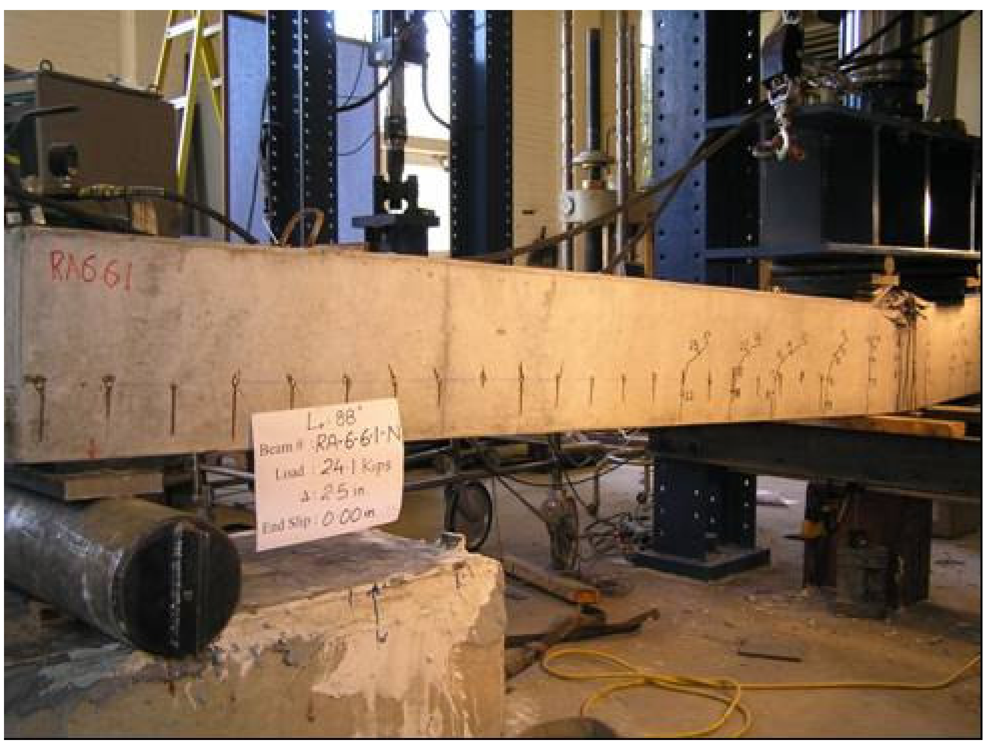
Concrete crushing failure was observed at 24.1 kips (deflection = 2.5 in.) with concrete between the two point loads spalling off. Deflection was continued to increase till the total deflection reached 5.5 in.

End-slip reading at both the ends remained 0.000 in. throughout the loading and unloading cycles.

Cracking pattern shows 13 cracks in the middle 90 in. span with the average crack spacing of 7.5 in. No inclined flexural crack was observed. Crack width of the central crack was ½ in.



(For the above graph intermediate points for unloading curve could not be noted)



Cracking pattern for Beam RA-6-6-1 being loaded at North end

BEAM NAME: RA-6-6-2
END: NORTH
DATE: 08/18/2005

TEST PARAMETERS	
Concrete Compressive Strength	**8040 psi**
Embedment Length(L_e)	**73 in.**
Span	**162 in.**
Failure Mode	**Flexure**
Maximum Load	**29.0 kips**
Maximum Moment	**1001 kip-in**
Deflection @ Failure	**2.1 in.**
Maximum deflection attained	**2.7 in.**
Rebound after complete unloading	**2.3 in.**
Average Transfer Length (L_t) @ release	**31.7 in.**
@ time of testing	**52.2 in.**
Average NASP P.O value for strand 0.6 in."A"	**18.29 kips**

TEST SUMMARY

Load was applied in approximately 1.5 kips increments till first flexural cracking. Beyond this point the deflection was incremented by 0.03 in. till total deflection reached 1.00 in. Further increments of deflection were kept 0.05 in. up to 2.0 in. From this point deflection increments were set to 0.1 in.

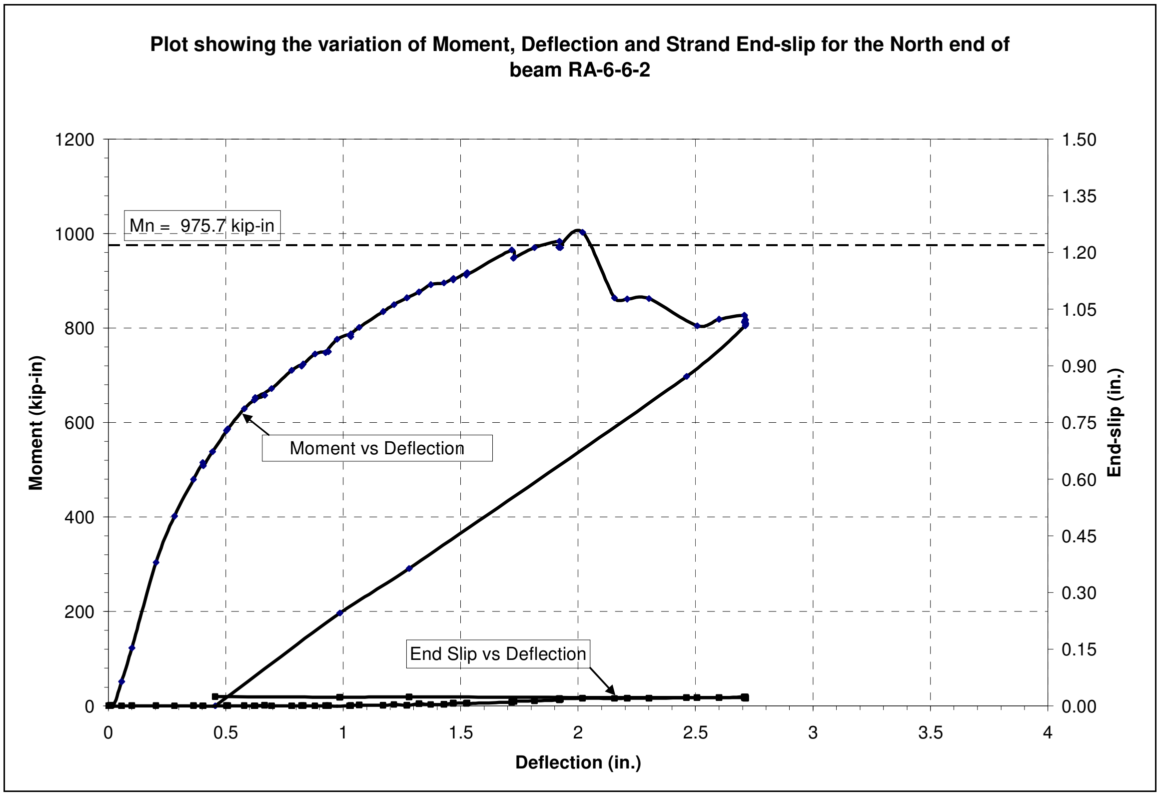
First flexural crack was observed at 15.1 kips at deflection of 0.4 in. First flexural cracks were observed as two pairs located symmetrically about the midpoint plus one crack at the approximately midpoint.

As the load reached 21.7 kips (0.9 in deflection) a sudden inclined flexural crack was observed with a jerk at Stn. 36. No end-slip was noticed at this load and deflection.First end-slip of 0.01 in. was observed at 26.2 kips. (deflection = 1.4 in.). End-slip at the South end remained at 0.000 in.

The first flexural crack from the North end showed another crack growing horizontally towards the North end approximately 3in. from the bottom surface.

Concrete crushing failure was observed at 29.1 kips (deflection = 2.1in.). End slip at this load and deflection was 0.02 in.

Cracking pattern included 10 cracks in the middle 71 in. span with the average crack spacing of 7.9 in. Distance between the first flexural crack and inclined flexural crack was 19 in. Inclined flexural crack was located at Stn. 36.Maximum end-slip at deflection of 2.7 in was 0.03 in.



Cracking pattern for Beam RA-6-6-2 being loaded at North end

BEAM NAME: RA-6-6-2
END: NORTH
DATE: 08/19/2005

TEST PARAMETERS	
Concrete Compressive Strength	**8040 psi**
Embedment Length(L_e)	**58 in.**
Span	**148 in.**
Failure Mode	**Bond**
Maximum Load	**33.8 kips**
Maximum Moment	**912.6 kip-in**
Deflection @ Failure	**2.1 in.**
Rebound after complete unloading	**1.7 in.**
Average Transfer Length (L_t) @ release	**30.1 in.**
@ time of testing	**49.4 in.**
Average NASP P.O value for strand 0.6 in."A"	**18.29 kips**

<u>TEST SUMMARY</u>

Load was applied in approximately 2.0 kips increments till first flexural cracking. Beyond this point the deflection was incremented by 0.03 in. till total deflection reached 1.00 in. Further increments of deflection were kept 0.05 in. up to 2.0 in. From this point deflection increments were set to 0.1 in.

First flexural crack was observed at 20.2 kips at deflection of 0.5 in. First flexural cracks were formed as a pair of cracks located symmetrically about the midpoint.

As the load reached 20.4 kips (0.6 in deflection), a sudden inclined flexural crack was observed at Stn. 38. First end-slip of 0.01 in. was noticed at 23.4 kips (deflection = 0.8 in.)

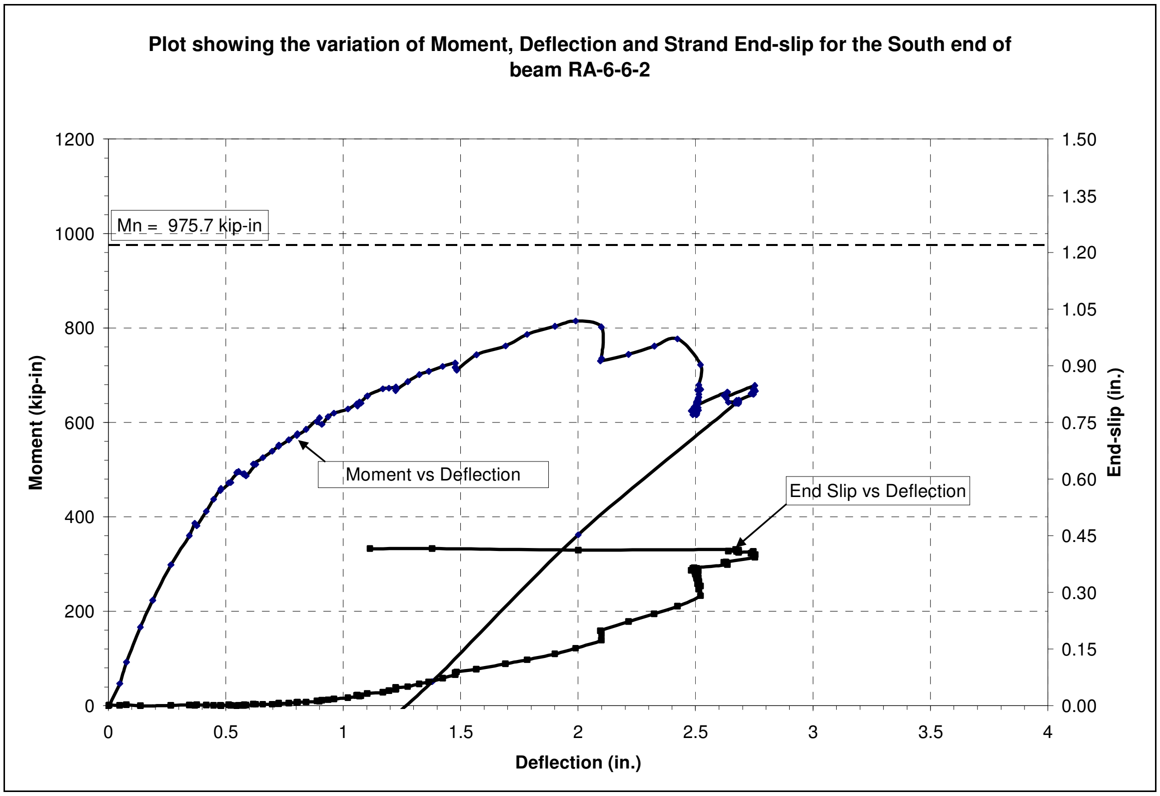
More flexural cracks continued to form at further increments in the flexural zone even after an inclined flexural crack was formed in the shear zone. Cracking became audible at 27 kips (deflection = 1.2 in.).

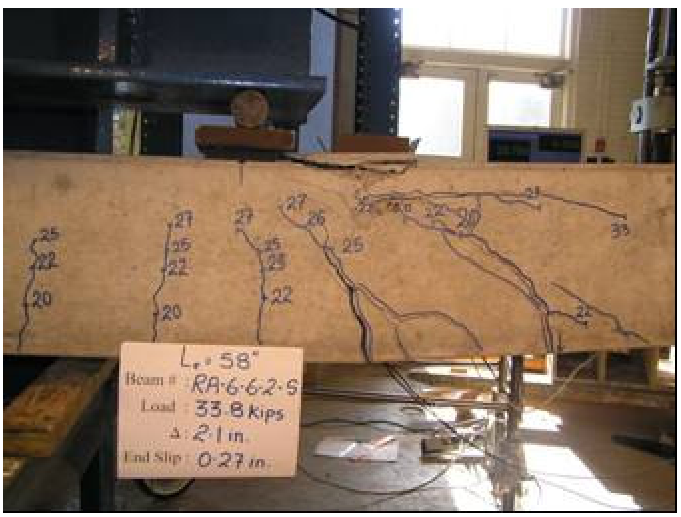
Inclined flexural crack started widening considerably after load of 27.9 kips (deflection = 1.3 in.). At 30.0 kips (deflection = 1.6 in.) a crack parallel to the inclined flexural crack was observed at a distance approximately 1.5 in from the inclined flexural crack.

Maximum load reached was 33.8 kips. (at deflection = 2.1 in.; end slip = 0.16 in.). At this load and deflection it was noticed that the first flexural crack after the inclined flexural crack grew in width. Deflection increments were continued up to total deflection of 2.7 in.

At 31.2 kips (deflection of 2.5 in.) a brief halt of approximately 10 minutes was taken for some laboratory adjustments. Maximum end-slip noted at deflection of 2.7 in. was 0.41 in.

Cracking pattern included 10 cracks in the middle 54 in. span with average crack spacing of 6in. Inclined flexural crack first formed at Stn. 38 bifurcated to touch the bottom surface at Stn. 31. Crushing of concrete was evident outside of the constant moment region.





Concrete crushing observed outside the constant moment region.

Cracking pattern for Beam RA-6-6-2 being loaded at South end

BEAM NAME: RA-6-6-3
END: NORTH
DATE: 08/24/2005

TEST PARAMETERS	
Concrete Compressive Strength	**8040 psi**
Embedment Length(L_e)	**88 in.**
Span	**192 in.**
Failure Mode	**Flexure**
Maximum Load	**24.9 kips**
Maximum Moment	**1046 kip-in**
Deflection @ Failure	**2.6 in.**
Maximum deflection attained	**4.0 in.**
Rebound after complete unloading	**2.8 in.**
Average Transfer Length (L_t) @ release	**25.8 in.**
@ time of testing	**45.0 in.**
Average NASP P.O value for strand 0.6in."A"	**18.29 kips**

<u>TEST SUMMARY</u>

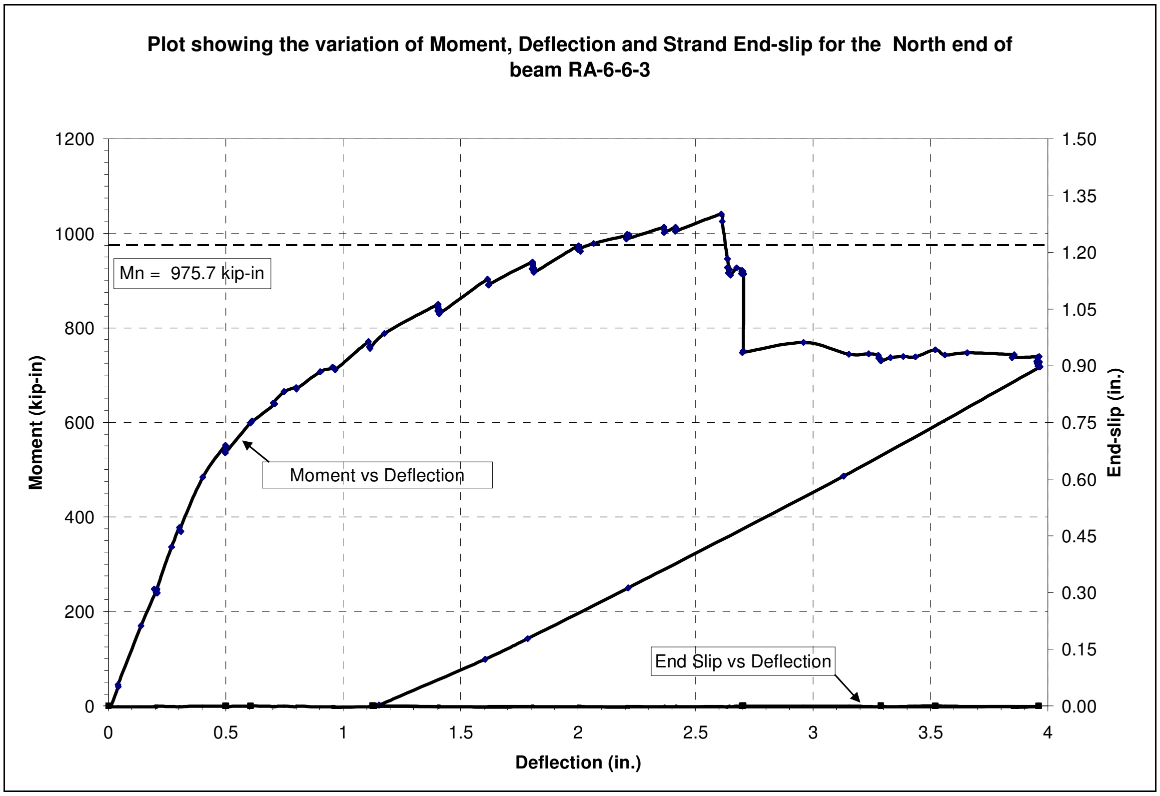
Load was applied in approximately 1.5 kips increments till first flexural cracking. Beyond this point the deflection was incremented by 0.03 in. till total deflection reached 1.00 in. Further increments of deflection were kept 0.05 in. up to 2.0 in. From this point deflection increments were set to 0.1 in.

First flexural crack was observed at 13.3 kips at deflection of 0.5 in. The first flexural cracks were formed in the form of two pairs located symmetrically about the midpoint.

Concrete crushing failure was observed at 24.9 kips (deflection = 2.6 in.) at the top surface of concrete in the constant moment region.

End-slip values throughout the loading and unloading cycles remained at 0.000 in.

Cracking pattern included 15 cracks in the middle 101 in. span with average crack spacing of 7.2 in. No inclined flexural crack was observed. The first flexural crack was observed at Stn. 50.



Cracking pattern for Beam RA-6-6-3 being loaded at North end

BEAM NAME: RA-8-6-1
END: NORTH
DATE: 08/19/2005

TEST PARAMETERS	
Concrete Compressive Strength	**8040 psi**
Embedment Length(L_e)	**88 in.**
Span	**208 in.**
Failure Mode	**Flexure**
Maximum Load	**24.0 kips**
Maximum Moment	**1008 kip-in**
Deflection @ Failure	**2.4 in.**
Maximum defletion attained	**3.5 in.**
Rebound after complete unloading	**2.7 in.**
Average Transfer Length (L_t) @ release	**28.2 in.**
@ time of testing	**45.5 in.**
Average NASP P.O value for strand 0.6 in."A"	**18.29 kips**

TEST SUMMARY

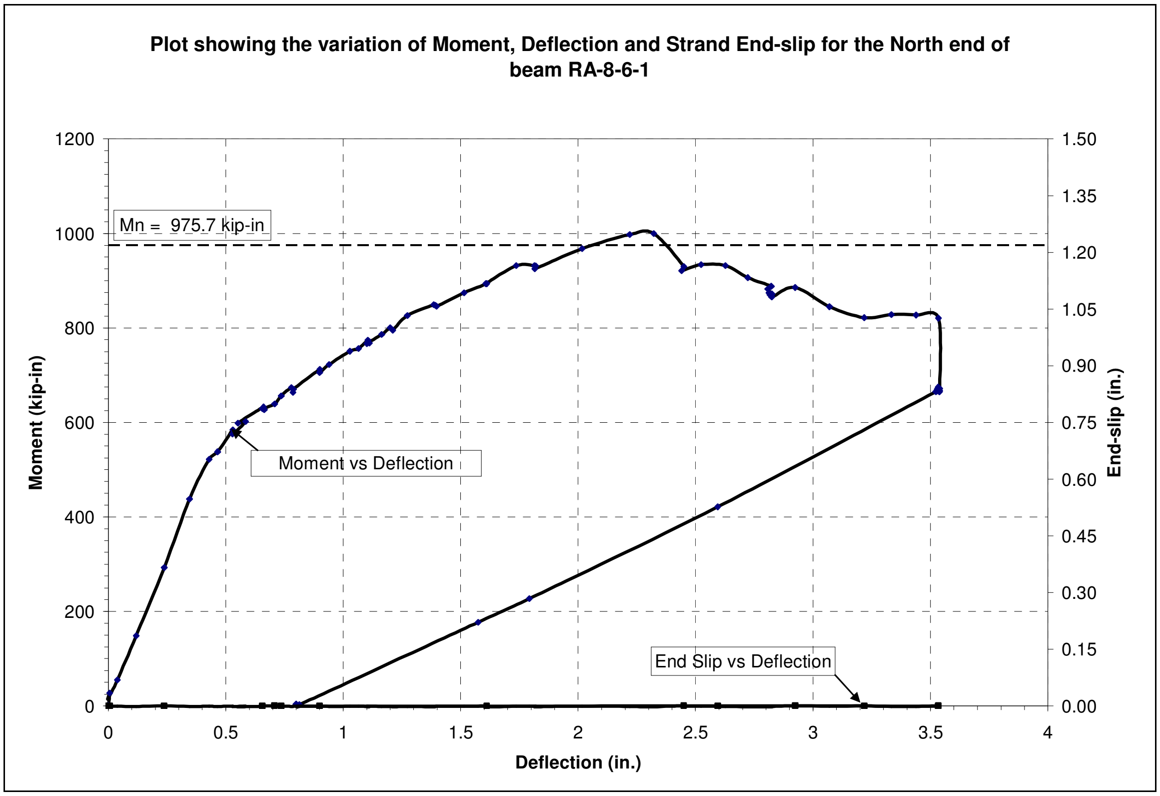
Load was applied in approximately 1.0 kips increments till first flexural cracking. Beyond this point the deflection was incremented by 0.03 in. till total deflection reached 1.00 in. Further increments of deflection were kept 0.05 in. up to 2.0 in. From this point deflection increments were set to 0.1 in.

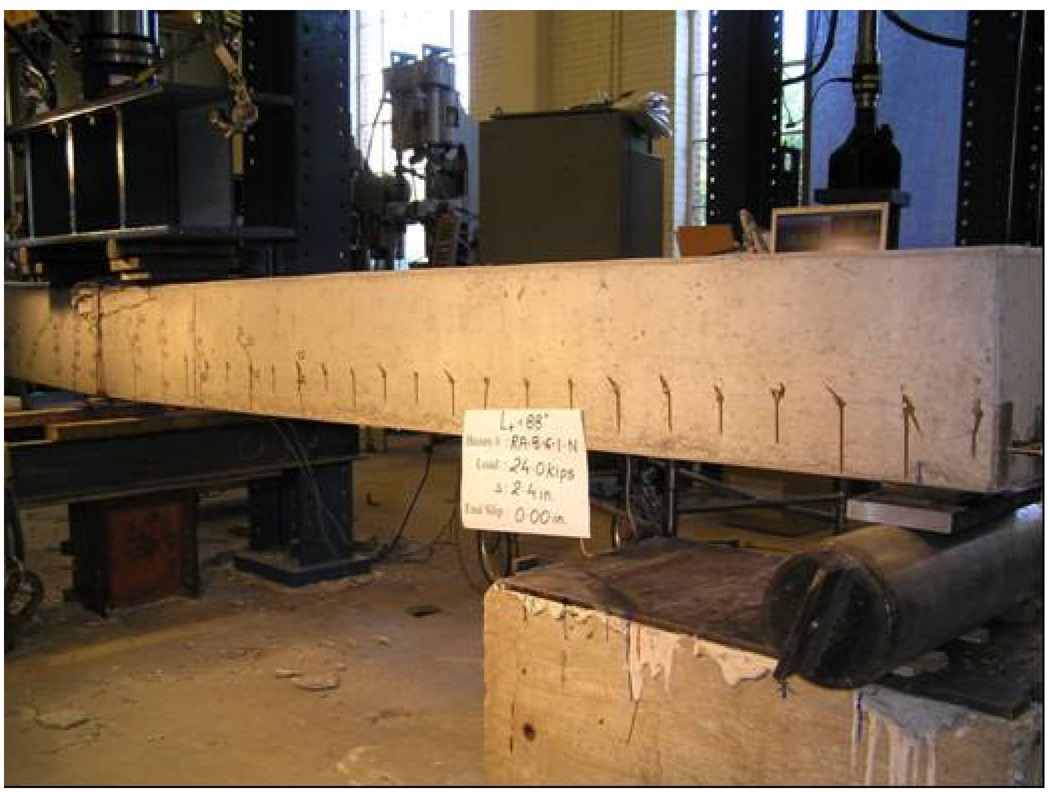
First flexural crack was observed at 13.4 kips at deflection of 0.6 in. First flexural cracks were formed as three pairs of cracks located symmetrically about the midpoint.

No significant changes were observed till the load reached 24.0 kips (deflection = 2.4 in.) where concrete crushing failure was observed at the top surface. Crushed concrete zone lied in the constant moment region. End-slip at failure remained 0.00 in.

No inclined flexural crack was observed. The cracking pattern included 11 cracks in the middle 82 in. span with average crack spacing of 8.2 in. The first flexural crack was located at Stn. 59.

Maximum deflection attained was 3.5 in. and end-slip throughout the loading and unloading cycle remained 0.00 in at both ends.





Cracking pattern for Beam RA-8-6-1 being loaded at North end

BEAM NAME: RA-8-6-2
END: NORTH
DATE: 08/22/2005

TEST PARAMETERS	
Concrete Compressive Strength	**8220 psi**
Embedment Length(L_e)	**73 in.**
Span	**162 in.**
Failure Mode	**Flexure**
Maximum Load	**29.2 kips**
Maximum Moment	**1007 kip-in**
Deflection @ Failure	**2.0 in.**
Maximum Deflection attained	**2.8 in.**
Rebound after complete unloading	**2.2 in.**
Average Transfer Length (L_t) @ release	**28.2 in.**
@ time of testing	**46.4 in.**
Average NASP P.O value for strand 0.6in."A"	**18.29 kips**

<u>TEST SUMMARY</u>

Load was applied in approximately 1.5 kips increments till first flexural cracking. Beyond this point the deflection was incremented by 0.03 in. till total deflection reached 1.00 in. Further increments of deflection were kept 0.05 in. up to 2.0 in. From this point deflection increments were set to 0.1 in.

First flexural crack was observed at 16.4 kips at deflection of 0.4 in. First flexural cracks were noticed in the form of two pairs of cracks located symmetrically about the midpoint and in addition a central crack located approximately at the midpoint.

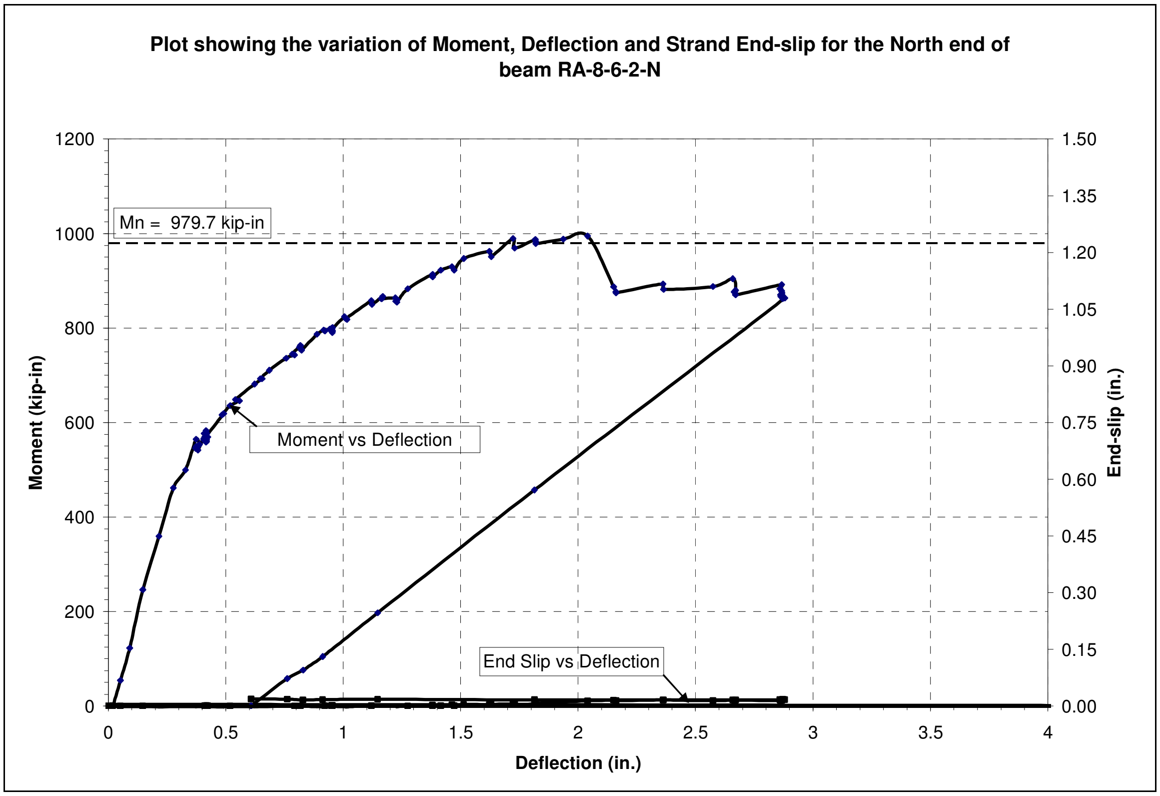
Cracks became audible at the load of 23 kips (deflection = 0.9 in.).

At 25 kips (deflection = 1.2 in.) a sudden inclined flexural crack was noticed at Stn. 38. First end-slip of 0.01 in. was observed at 28.2 kips (deflection = 1.7 in.). Another crack was visible along the side of the inclined flexural crack at approx. 1.5 in from the inclined flexural crack at 28.9 kips (deflection = 1.9 in.)

Concrete crushing failure was identified at the load of 29.2 kips (deflection = 2.0 in.) with the top surface of concrete crushed in the constant moment region. End-slip at failure was 0.01 in.

Cracking pattern included 11 cracks in the middle 73 in span with average crack spacing of 7.3 in. Inclined flexural crack was at Stn. 38, with the lower end bifurcated without touching the bottom surface approx. 3 in from bottom. End-slip at the south end remained

0.000 in. throughout the loading and unloading cycles. Maximum end-slip at the deflection of 2.8 in was 0.02 in.



Cracking pattern for Beam RA-8-6-2 being loaded at North end

BEAM NAME: RA-8-6-2
END: SOUTH
DATE: 08/22/2005

TEST PARAMETERS	
Concrete Compressive Strength	**8220 psi**
Embedment Length(L_e)	**58 in.**
Span	**132 in.**
Failure Mode	**Bond**
Maximum Load	**36.6 kips**
Maximum Moment	**988 kip-in**
Deflection @ Failure	**2.5 in.**
Rebound after complete unloading	**2.2 in.**
Average Transfer Length (L_t) @ release	**25.7 in.**
@ time of testing	**42.4 in.**
Average NASP P.O value for strand 0.6 in."A"	**18.29 kips**

TEST SUMMARY

Load was applied in approximately 1.5 kips increments till first flexural cracking. Beyond this point the deflection was incremented by 0.03 in. till total deflection reached 1.00 in. Further increments of deflection were kept 0.05 in. up to 2.0 in. From this point deflection increments were set to 0.1 in.

First flexural crack was observed at 21.2 kips at deflection of 0.6 in. First flexural cracks were noticed in the form of four pairs of cracks with cracks at the North side rising from the pre-existing cracks formed during the North end testing.

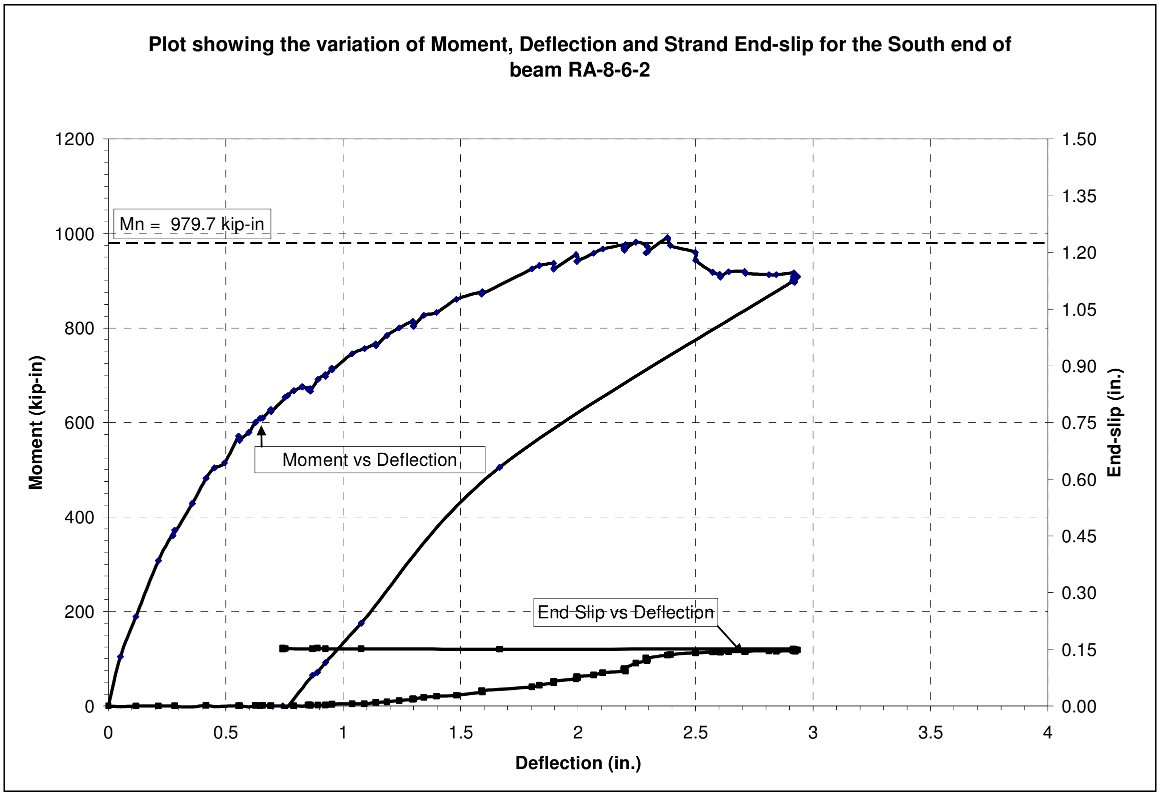
At 25.1 kips (deflection = 0.9 in.) a sudden inclined flexural crack was observed at Stn. 31 with a loud noise. First end-slip of 0.1 in was observed at 26.4 kips (deflection = 1.0 in.)

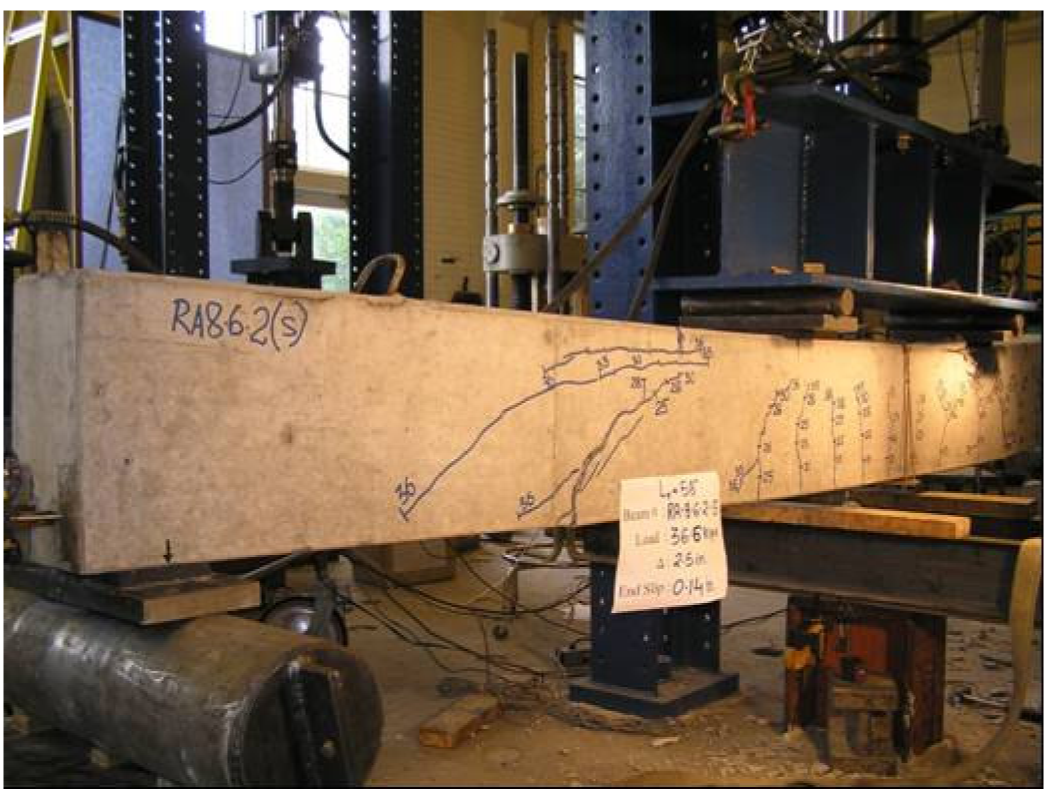
A second inclined flexural crack was formed at Stn. 18 but did not touch the bottom surface of the beam. This crack started from the topmost point of the first inclined flexural crack and then went on to propagate diagonally downwards.

Crushing of concrete was observed at 36.6 kips(deflection = 2.5 in.) At this point the moment was almost equal but slightly less (988 kip-in) than the nominal moment (989 kip-in). The failure was thus declared to be a bond failure. End-slip reading at this point was 0.12 in.

Cracking pattern included 6 cracks in the 27 in. span towards the South end with average crack spacing of 5.4 in. Maximum end-slip at the deflection of 2.9 in. was 0.15 in.

End-slip at the North end remained 0.000 in throughout the loading and unloading cycle.





Cracking pattern for Beam RA-8-6-2 being loaded at South end

BEAM NAME: RA-10-6-1
END: NORTH
DATE: 08/24/2005

TEST PARAMETERS	
Concrete Compressive Strength	**14610 psi**
Embedment Length(L_e)	**88 in.**
Span	**192 in.**
Failure Mode	**Flexure**
Maximum Load	**25.8 kips**
Maximum Moment	**1084 kip-in**
Deflection @ Failure	**2.8 in.**
Maximum defletion attained	**5.0 in.**
Rebound after complete unloading	**2.8 in.**
Average Transfer Length (L_t) @ release	**20.0 in.**
@ time of testing	**30.0 in.**
Average NASP P.O value for strand 0.6in."A"	**18.29 kips**

<u>TEST SUMMARY</u>

Load was applied in approximately 1.0 kips increments till first flexural cracking. Beyond this point the deflection was incremented by 0.03 in. till total deflection reached 1.00 in. Further increments of deflection were kept 0.05 in. up to 2.0 in. From this point deflection increments were set to 0.1 in.

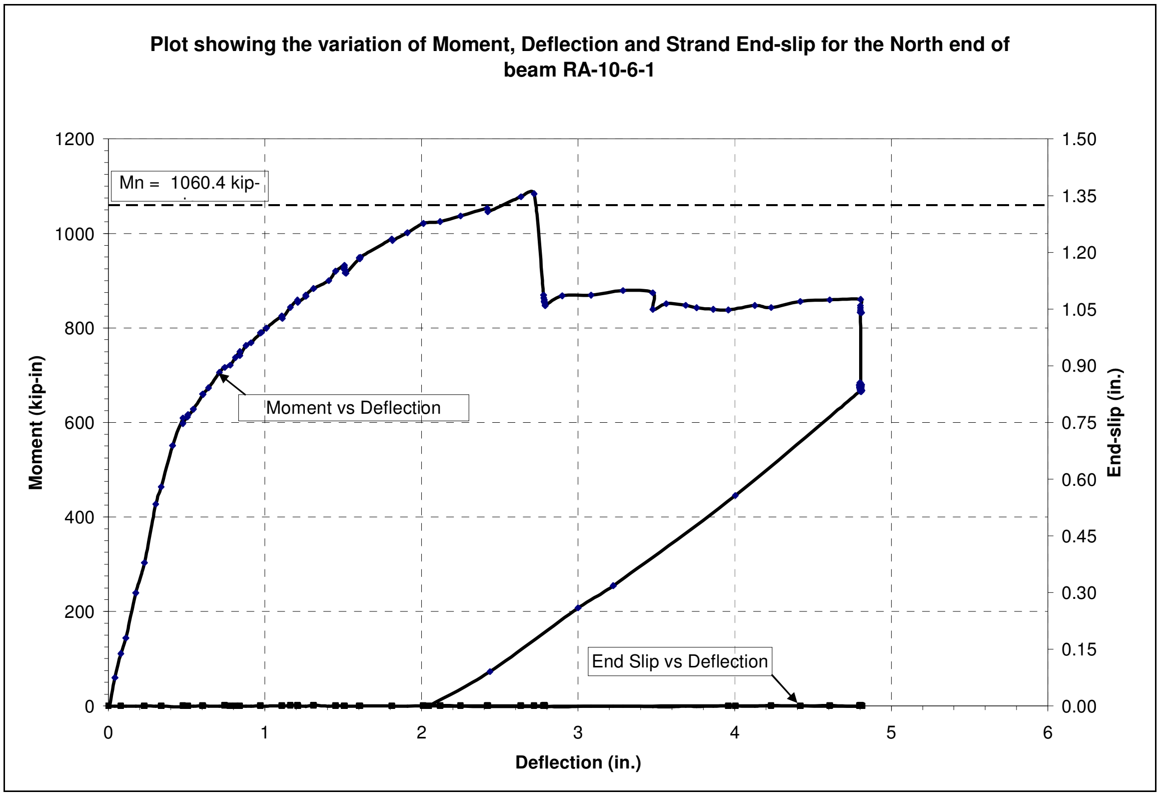
First flexural crack was observed at 14.9 kips at deflection of 0.5 in. First flexural cracks were formed in the form of two pairs of cracks located symmetrically about the midpoint in addition to the central crack.

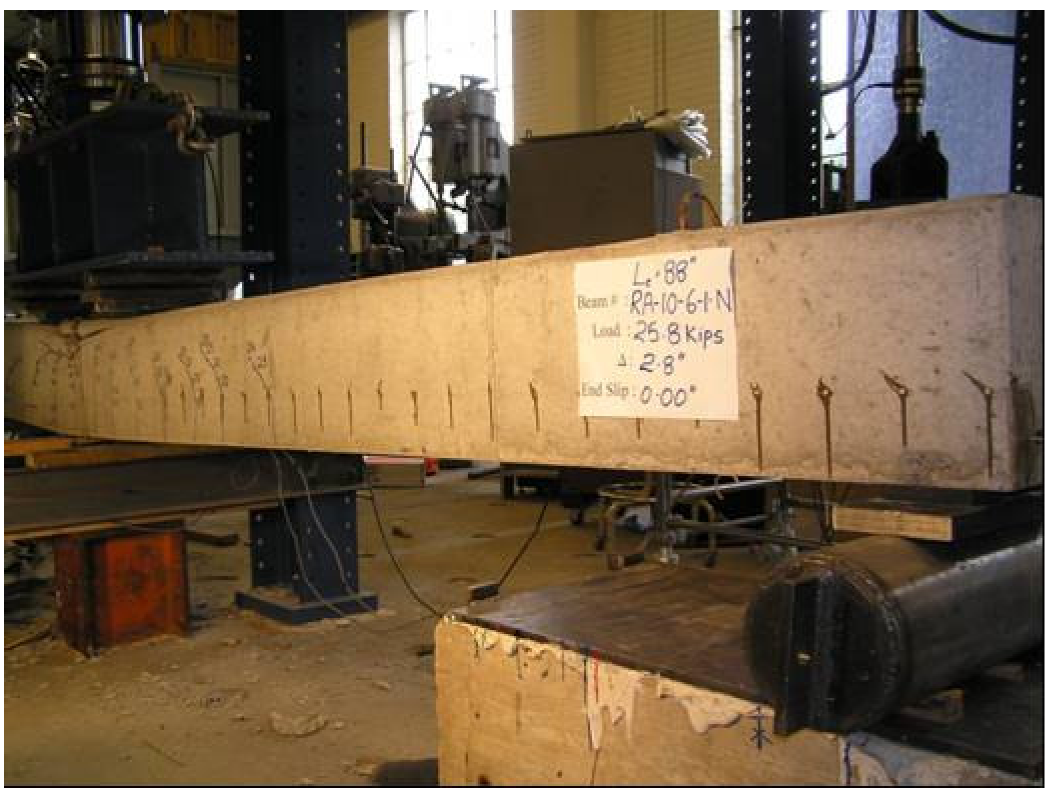
A secondary crack was formed between the second and third crack towards the North side from the central crack at the load of 19.0 kips (deflection = 0.9 in.)

Concrete crushing failure was observed at 25.8 kips (deflection = 2.8 in.) at the top surface of concrete within the constant moment region. The deflection increments were continued till the total deflection reached 5.0 in.

End-slip at both ends remained 0.00 in. throughout the loading and unloading cycles.

Cracking pattern included 13 cracks in the middle 84 in. span with the average crack spacing of 7 in. No inclined flexural crack was observed. The first flexural crack was located at the St. 59.





Cracking pattern for Beam RA-10-6-1 being loaded at North end

BEAM NAME: RA-10-6-2
END: NORTH
DATE: 08/24/2005

TEST PARAMETERS	
Concrete Compressive Strength	**14610 psi**
Embedment Length(L_e)	**73 in.**
Span	**162 in.**
Failure Mode	**Flexure**
Maximum Load	**31.0 kips**
Maximum Moment	**1070 kip-in**
Deflection @ Failure	**1.8 in.**
Maximum deflection attained	**2.5 in.**
Rebound after complete unloading	**2.0 in.**
Average Transfer Length (L_t) @ release	**15.6 in.**
@ time of testing	**26.8 in.**
Average NASP P.O value for strand 0.6in."A"	**18.29 kips**

TEST SUMMARY

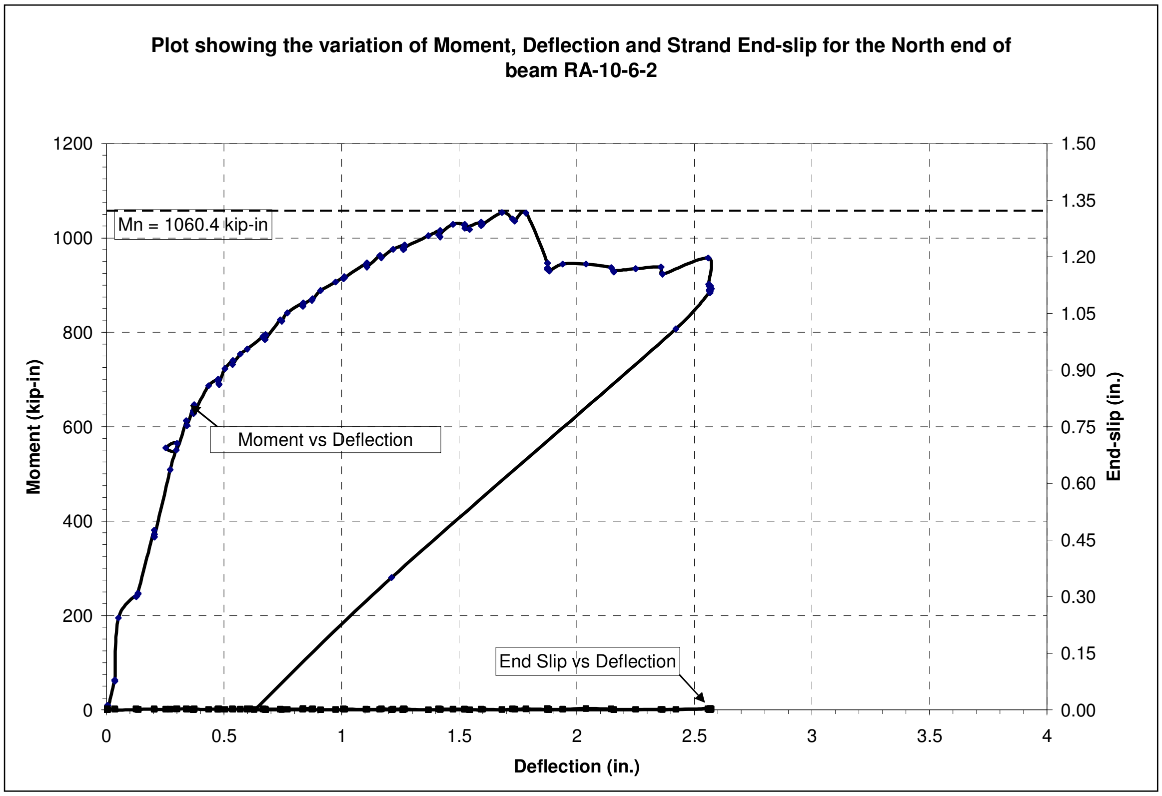
Load was applied in approximately 1.5 kips increments till first flexural cracking. Beyond this point the deflection was incremented by 0.03 in. till total deflection reached 1.00 in. Further increments of deflection were kept 0.05 in. up to 2.0 in. From this point deflection increments were set to 0.1 in.

First flexural crack was observed at 18.6 kips at deflection of 0.4 in. First flexural cracks were formed in the form of a pair with one central crack.

No significant changes were noticed till the load reached 31.0 kips (deflection = 2.5 in.) when concrete crushing failure was observed at the top surface of concrete in the constant moment region.

End-slip values remained 0.000 in. at both ends throughout the loading and unloading cycles.

Cracking pattern included 9 cracks in the middle 70 in. span with the average crack spacing of 8.8 in. The first flexural crack was observed at Stn. 49. No inclined flexural crack was observed.



Cracking pattern for Beam RA-10-6-2 being loaded at North end

BEAM NAME: RA-10-6-2
END: SOUTH
DATE: 08/24/2005

TEST PARAMETERS	
Concrete Compressive Strength	**14610 psi**
Embedment Length(L_e)	**58 in.**
Span	**148 in.**
Failure Mode	**Flexure**
Maximum Load	**40.1 kips**
Maximum Moment	**1083 kip-in**
Deflection @ Failure	**2.4 in.**
Rebound after complete unloading	**2.2 in.**
Average Transfer Length (L_t) @ release	**21.8 in.**
@ time of testing	**30.7 in.**
Average NASP P.O value for strand 0.6in."A"	**18.29 kips**

TEST SUMMARY

Load was applied in approximately 2.0 kips increments till first flexural cracking. Beyond this point the deflection was incremented by 0.03 in. till total deflection reached 1.00 in. Further increments of deflection were kept 0.05 in. up to 2.0 in. From this point deflection increments were set to 0.1 in.

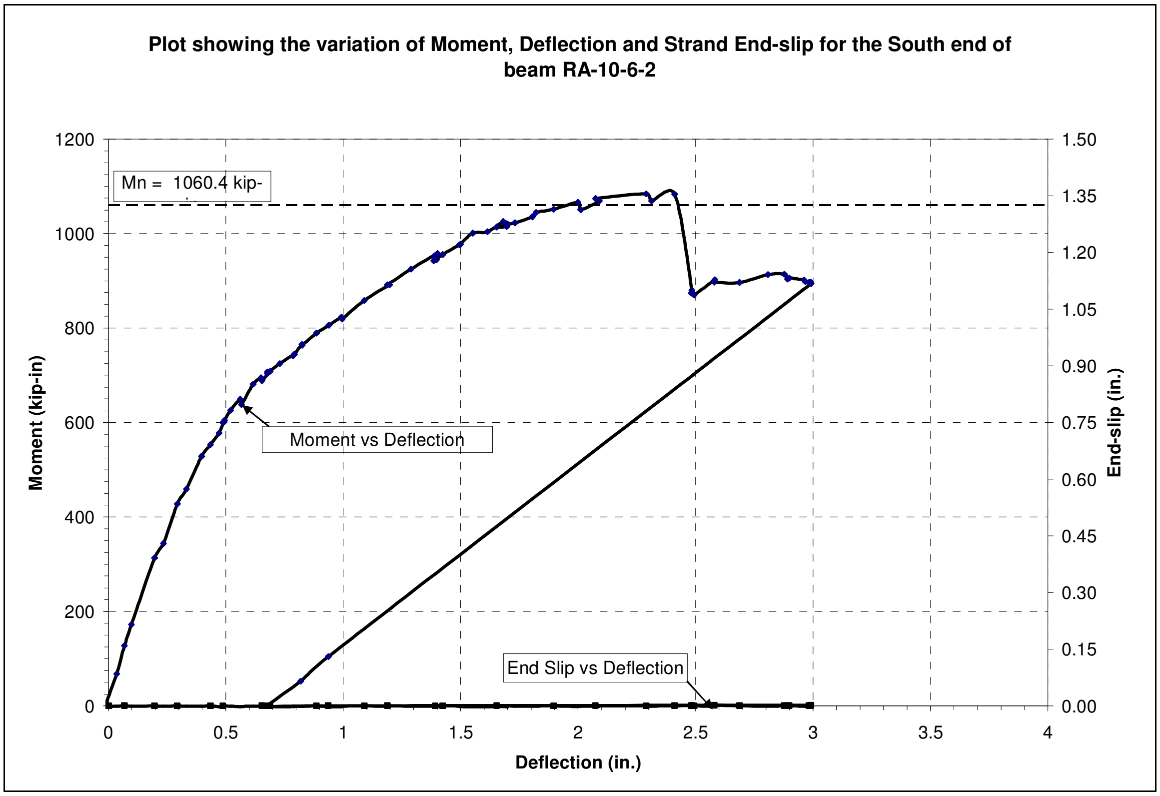
First flexural crack was observed at 22.3 kips at deflection of 0.5 in. First flexural cracks were formed in the form of two pairs of cracks located symmetrically about the midpoint.

At the load of 25.6 kips(deflection = 0.7 in.), a secondary crack was discovered at approximately the midpoint of the span.

Concrete crushing failure was observed with loud noise at the top surface of concrete in the constant moment region at 40.1 kips (deflection = 2.4 in.).

End-slip at all loads remained 0.00 in. at both ends.

Cracking pattern included 9 cracks in the middle 73 in. span with the average crack spacing of 9 in. No inclined flexural crack was noticed. First flexural crack was located at Stn. 41.



Cracking pattern for Beam RA-10-6-2 being loaded at South end

APPENDIX D

DEVELOPMENT LENGTH TEST SUMMARIES FOR I-SHAPED BEAMS WITH 0.5 IN. STRANDS

BEAM NAME: IB-6-5-1
END: NORTH
DATE: 09/02/2005

TEST PARAMETERS	
Concrete Compressive Strength	**9350 psi.**
Embedment Length(L_e)	**52 in.**
Span	**166 in.**
Failure Mode	**Failure did not occur**
Maximum Load	**117.4 kips**
Maximum Shear	**67.8 kips**
Maximum Moment	**3868.8 kip-in**
Maximum Deflection attained	**1.1 in.**
Rebound after complete unloading	**0.6 in.**
Average NASP P.O value for strand "B"	**20.21 kips**

	Transfer lengths (in.) for beam # IB-6-5-1		
		At Release	At the time of testing
North	Top	21.43	35.9
	Middle	16	22.63
	Bottom East	16.12	21.23
	Bottom Central	10.93	14.3
	Bottom West	17.82	23.76

TEST SUMMARY

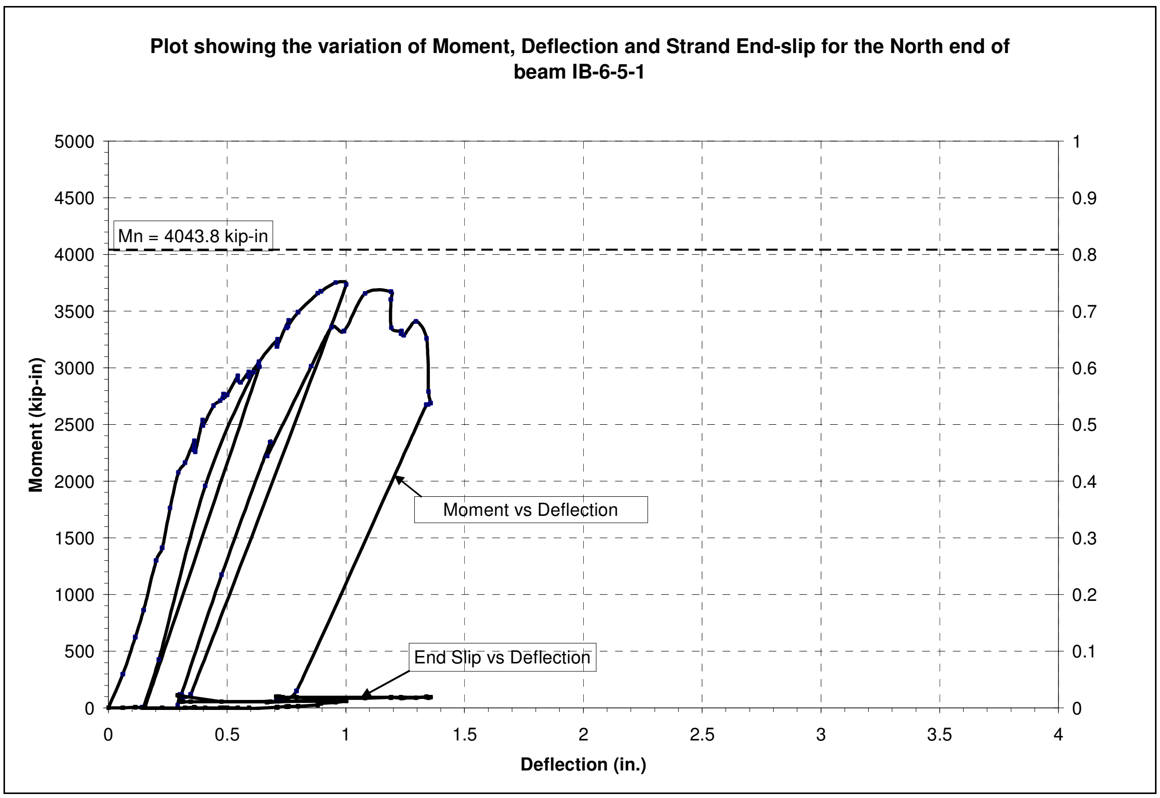
The beam was loaded in multiple cycles since parts of the setup had to be replaced during the loading cycles. For the first loading cycle, initial load increments were set at 3.0 kips till the first flexural cracking was observed. Beyond this point, the deflection was incremented by 0.020 in. For the subsequent loading cycles, the deflection increments were set to 0.1 in. DEMEC readings were taken during each increment.

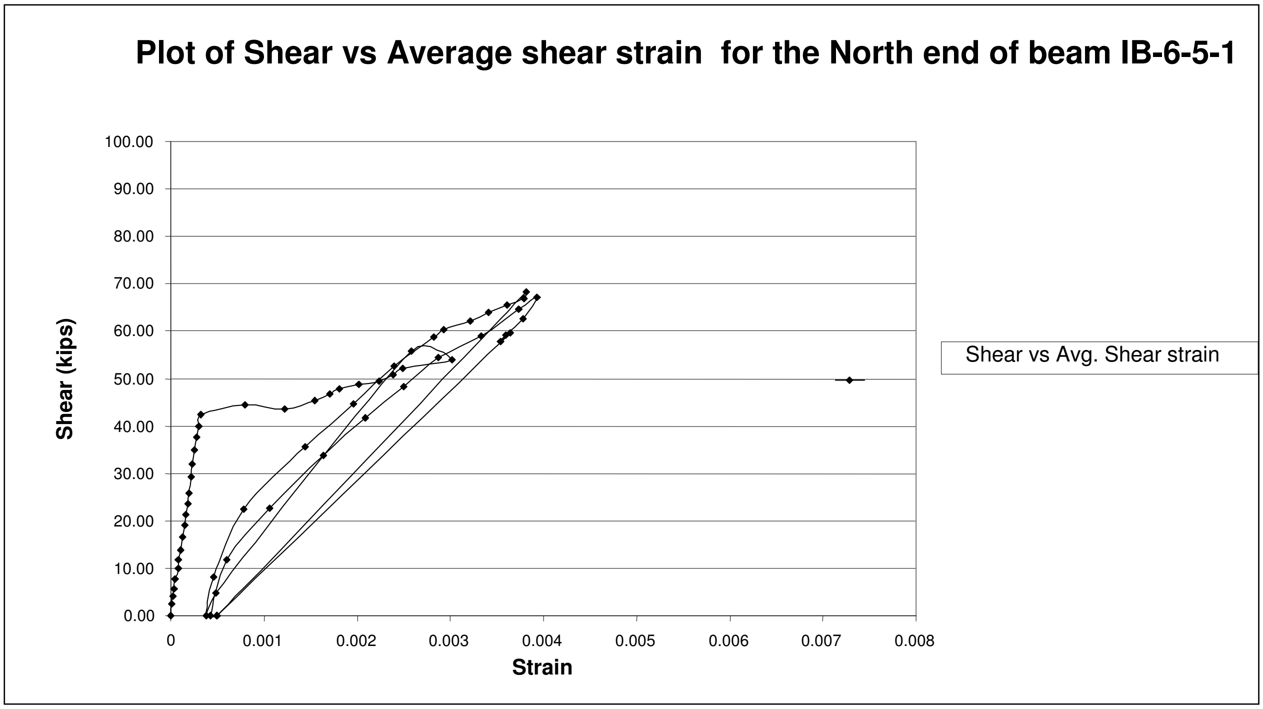
First flexural cracking was discovered at the load of 69.1 kips (Shear =40 kips; deflection = 0.34 in.). First flexural cracks were formed in the form of a pair of cracks located approximately below the two load points. First web shear cracks were noticed at the load of 76.7 kips (Shear = 44.3 kips; deflection = 0.37 in.). these web shear cracks were formed as a number of cracks fairly parallel to each other in the shear zone. The first and the last cracks from the North end were longer than those formed in between them. DEMEC readings were taken after the cracks were formed. A secondary crack was noticed at Stn. 60 at the laod of 82.7 kips (Shear = 47.8 kips; deflection = .46 in.). More secondary cracks continued to form throughout the loading cycle.

First end slip of 0.01 in was noticed at the load of 101.8 kips (Shear = 58.6 kips; deflection = 0.7 in.)

Cracks were clearly audible during the last loading cycle as the load reached 117.4 kips (Shear = 67.8kips; deflection = 0.9 in.) and the load dropped to 108.4 kips after the cracks were completely formed. The load value did not reach its maximum after this point, as for every further increment the load increased and dropped back with generation of audible cracks. It was noticed that the diagonal cracks were widening with each deflection increment. Finally a big cracking noise was heard which indicated either a strand wire fracture or the stirrup failure at the total deflection of 1.1 in. and it was decided to stop the loading cycle. The beam was unloaded and the DEMEC points as well as the deflection and end slip values were noted after complete unloading.

The value of end slip at the South end remained 0.00 in. throughout the loading and unloading cycles.





(In all the photographs presented below, cracks marked in black represent the ones originated as flexural cracks while those marked in blue represent the web shear cracks. Red color was used only for marking the grid lines and station points. Number written in red should not be confused with the load values.)

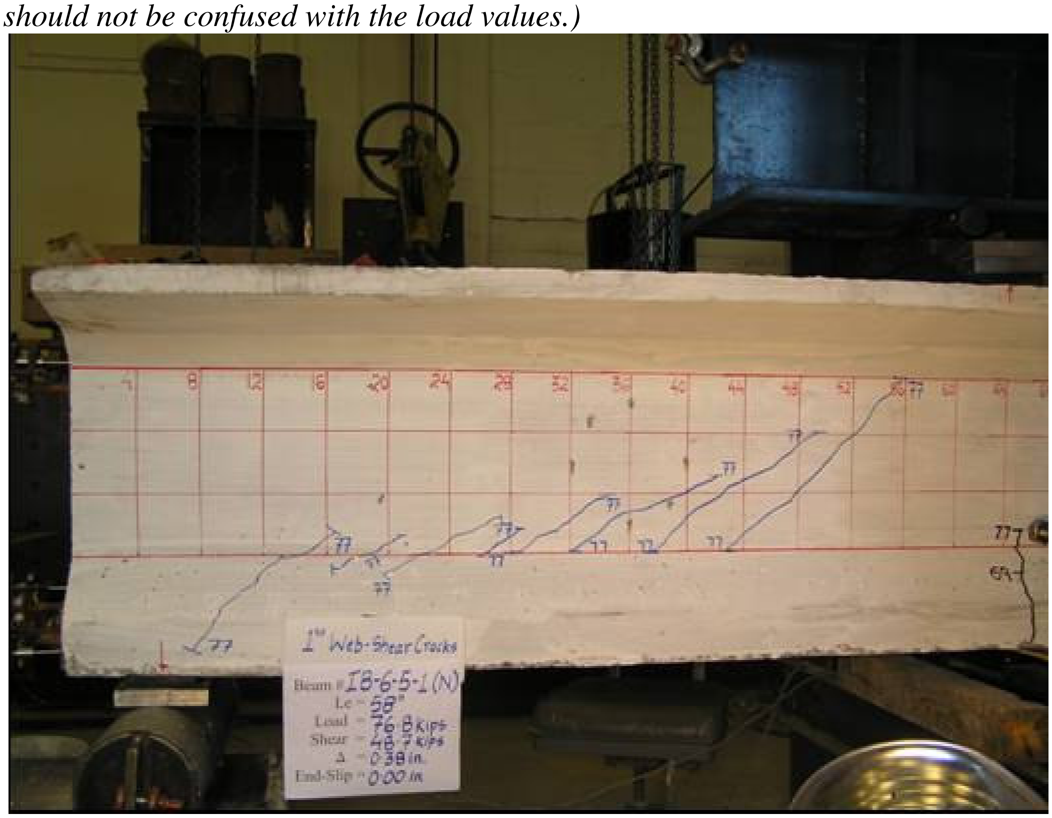


Photo of the North end of the beam IB-6-5-1 showing the first web shear cracking

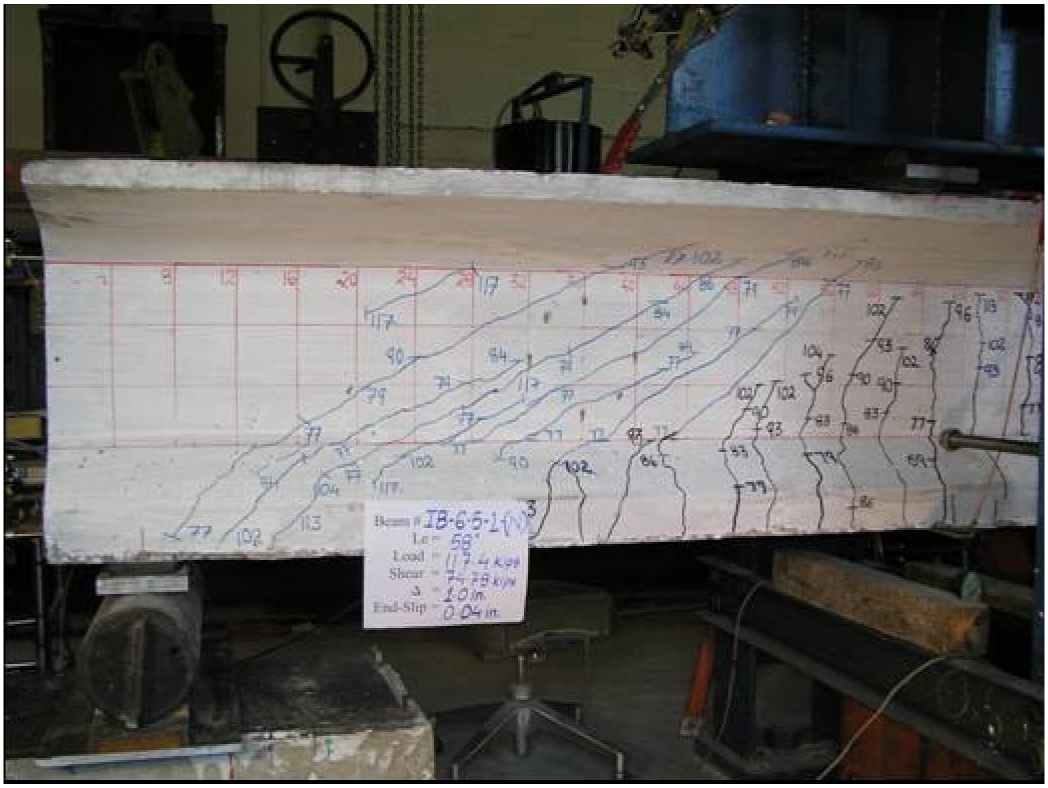


Photo of North end of beam IB-6-5-1 showing the cracking pattern at the maximum load

BEAM NAME: IB-6-5-1
END: SOUTH
DATE: 08/31/2005

TEST PARAMETERS	
Concrete Compressive Strength	**9350 psi**
Embedment Length(L_e)	**72 in.**
Span	**222 in.**
Failure Mode	**Flexure**
Maximum Load	**90.4 kips**
Maximum Shear	**60.3 kips**
Maximum Moment	**3979.8 kip-in.**
Maximum Deflection attained	**3.1 in.**
Rebound after complete unloading	**Deflection was not recovered**
Average NASP P.O value for strand "B"	**20.21 kips**

	Transfer lengths (in.) for beam # IB-6-5-1		
		At Release	At the time of testing
South	Top	6.16	23.04
	Middle	6.48	14.35
	Bottom East	6.42	13.11
	Bottom Central	9.45	16.19
	Bottom West	2.90	3.69

TEST SUMMARY

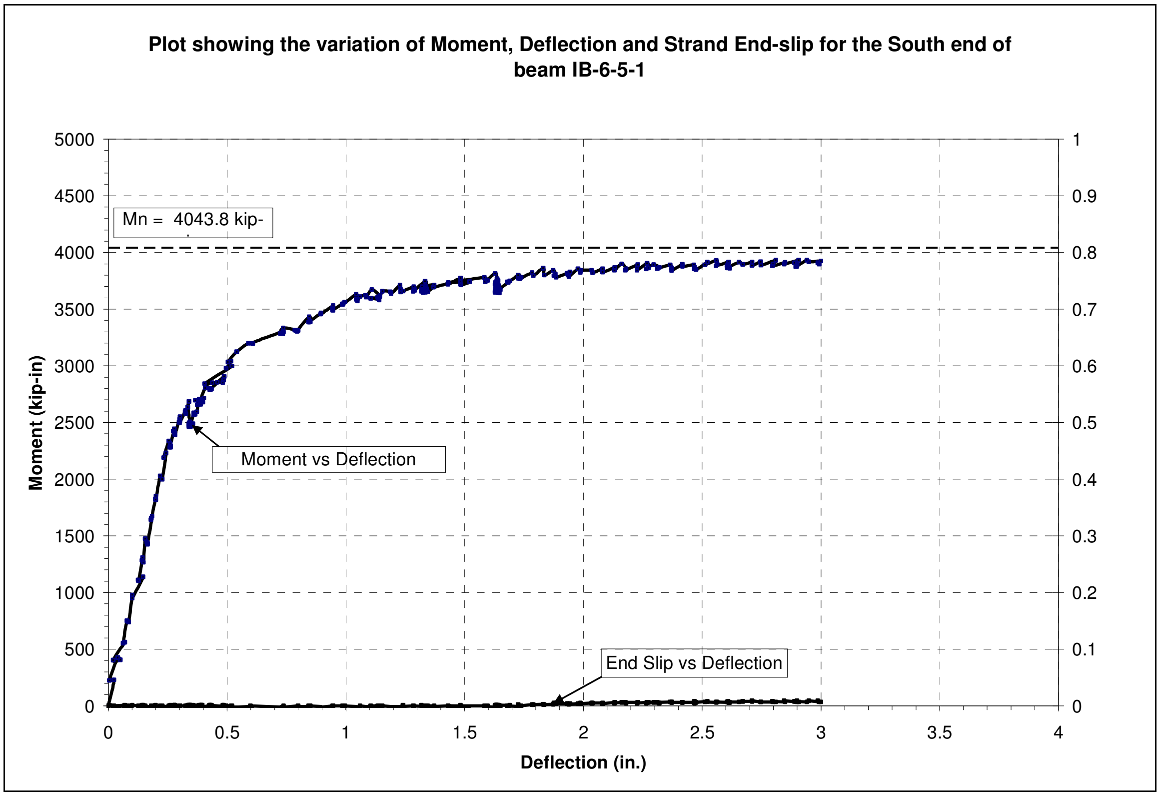
Load was applied in approximately 4.0 kips increments till first flexural cracking. Beyond this point the deflection was incremented by 0.025 in. till total deflection reached 0.4 in. Further increments of deflection were kept 0.05 in. DEMEC readings were taken at all load increments at both faces (East and West) with the rectangular rosette pattern at 36 in from the end being tested.

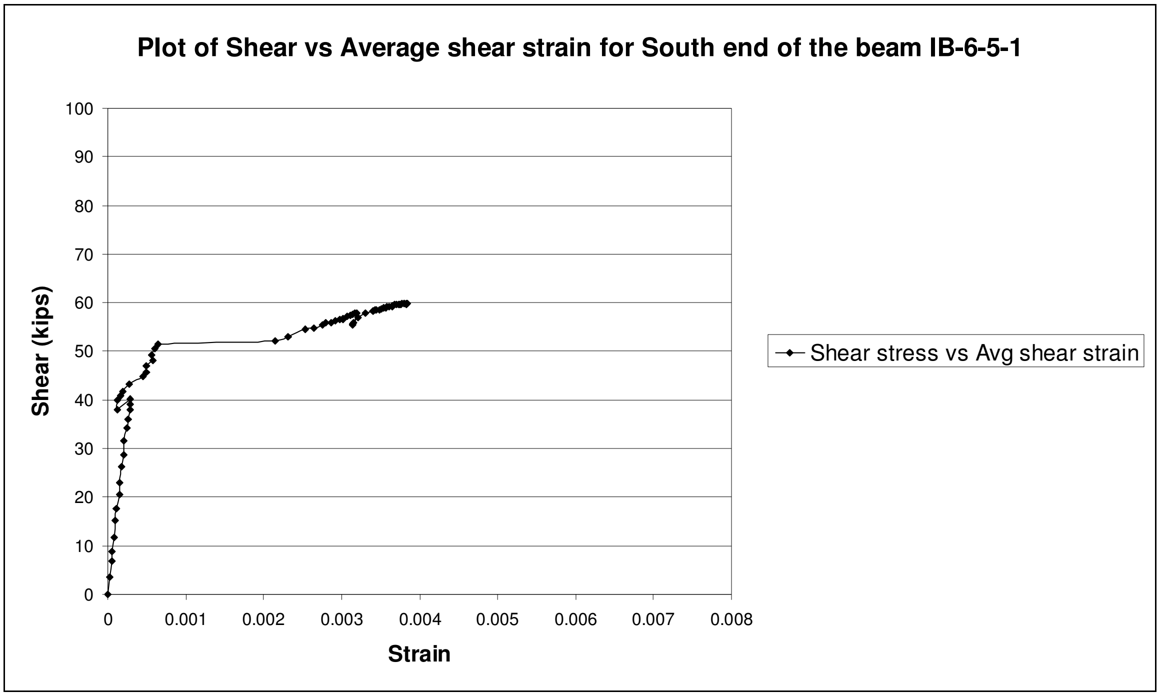
First flexural cracking was observed at the load of 54.1 kips (Shear = 36 kips; deflection = 0.26 in.) The first flexural crack was observed approximately at the mid span region approximately equidistant from the two point loads. At the load of 61.2 kips (Shear = 40.8 kips; deflection = 0.34 in.), while marking the new flexural cracks formed at that load, first web shear cracking occurred suddenly. The first web shear cracks were observed as a number of cracks almost parallel to each other and inclined diagonally with two of the innermost cracks longer than the rest. The load dropped to a value of 56.9 kips And the DEMEC readings were taken at the reduced value of load.

At 64.8 kips (Shear = 43.2 kips; deflection = 0.45 in) first secondary crack was noticed between Stn. 92 and Stn 96. More secondary cracks continued to form as the load increased further. Web shear cracks became audible beyond the load of 70.4 kips (Shear = 46.9 kips; deflection = 0.6 in.)

First end slip of 0.01 in. was noted at the load of 85.2 kips (Shear = 56.8 kips; deflection = 1.4 in.). The end slip value remained at 0.01 in. till failure occurred and at failure it suddenly increased to 0.025 in.

Concrete crushing failure was observed with a large sound at the load of 90.4 kips (Shear = 60.3 kips; deflection = 3.1 in.)





(In all the photographs presented below, cracks marked in black represent the ones originated as flexural cracks while those marked in blue represent the web shear cracks. Red color was used only for marking the grid lines and station points. Number written in red should not be confused with the load values.)

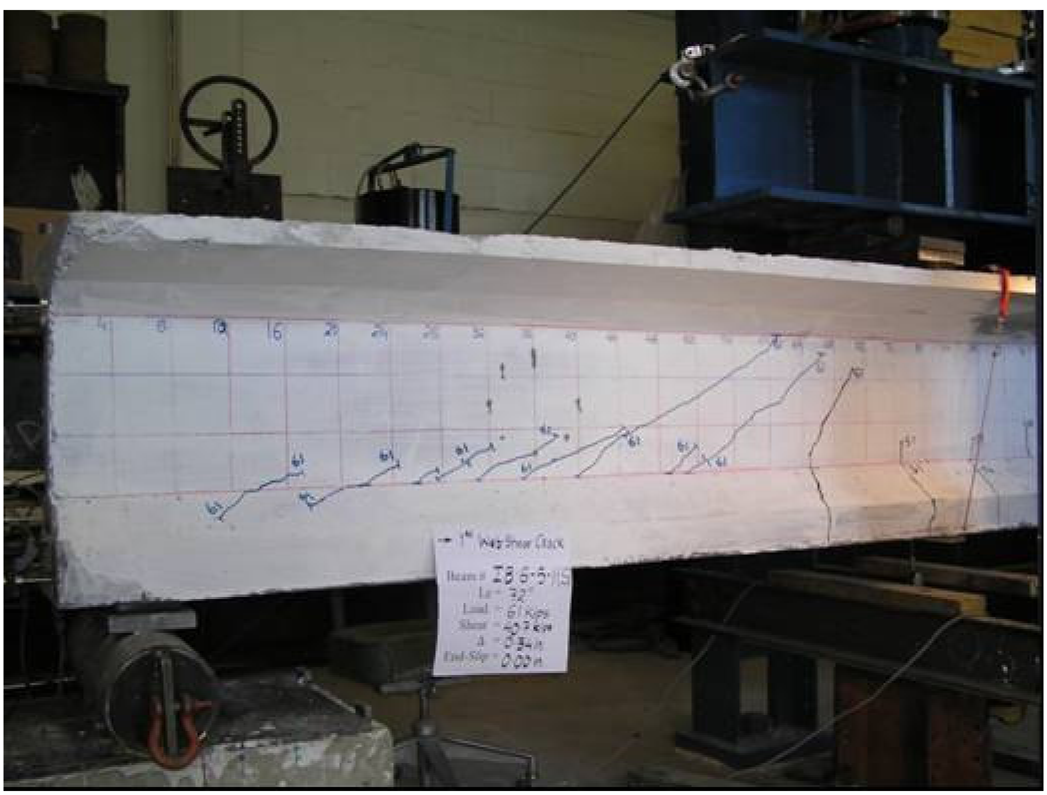


Photo of the South end of the beam IB-6-5-1 showing the first web shear cracking

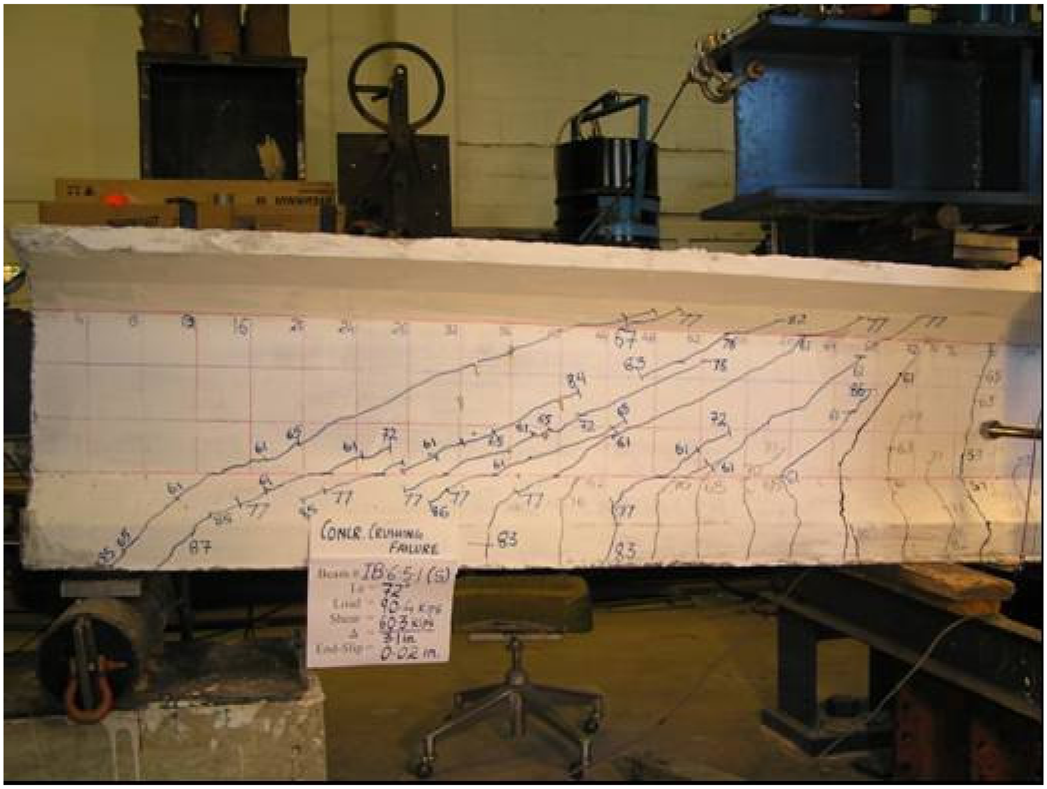


Photo of South end of beam IB-6-5-1 showing the cracking pattern at concrete crushing failure

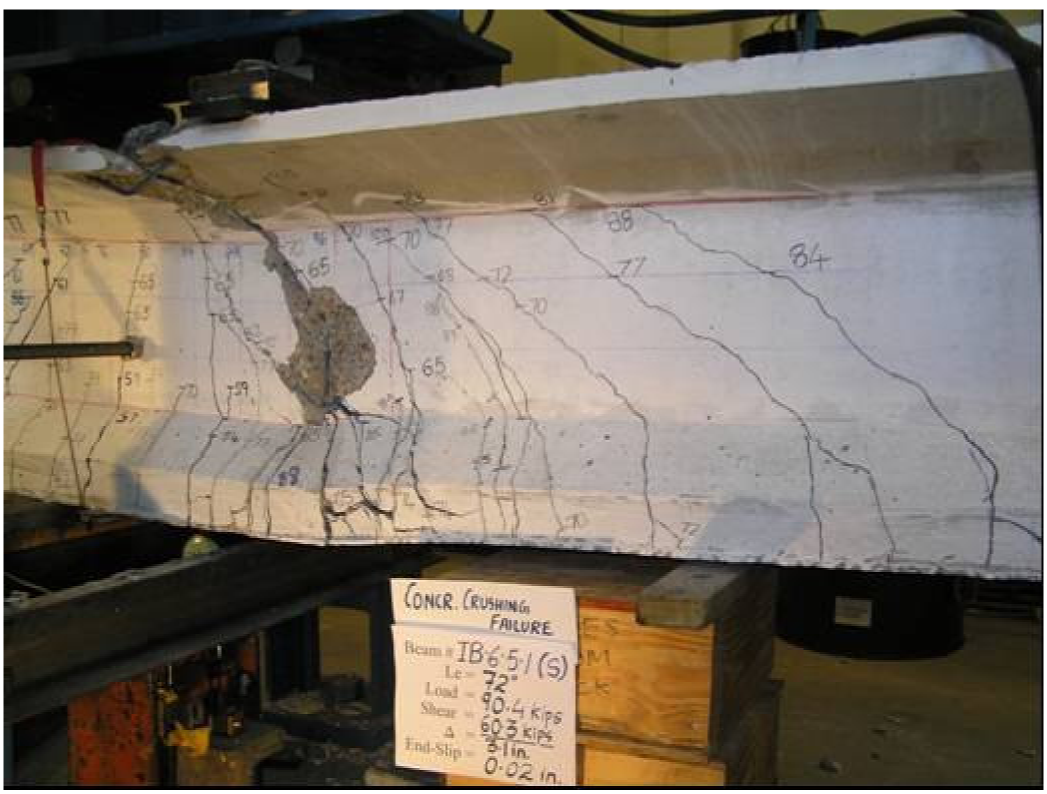


Photo of the crushed region of beam IB-6-5-1 (South end test)

BEAM NAME: IB-10-5-1
END: NORTH
DATE: 09/15/2005

TEST PARAMETERS	
Concrete Compressive Strength	**13490 psi**
Embedment Length(L_e)	**54 in.**
Span	**168 in.**
Failure Mode	**Failure did not occur**
Maximum Load	**133.8 kips**
Maximum Shear	**89.2 kips**
Maximum Moment	**4281.6 kip-in**
Maximum Deflection attained	**2.0 in.**
Rebound after complete unloading	**1.0 in.**
Average NASP P.O value for strand "B"	**20.21 kips**

	Transfer lengths (in.) for beam # IB-10-5-1		
		At Release	At the time of testing
North	Top	-	23.31
	Middle	11.31	15.73
	Bottom East	11.14	15.73
	Bottom Central	11.60	24.02
	Bottom West	10.03	19.54

<u>TEST SUMMARY</u>

Load was applied in approximately 6.0 kips increments till first flexural cracking. Beyond this point the deflection was incremented by 0.025 in. till total deflection reached 1.30 in. Further increments of deflection were kept 0.05 in. DEMEC readings were taken at all load increments at both faces (East and West) with the rectangular rosette pattern at 36 in from the end being tested.

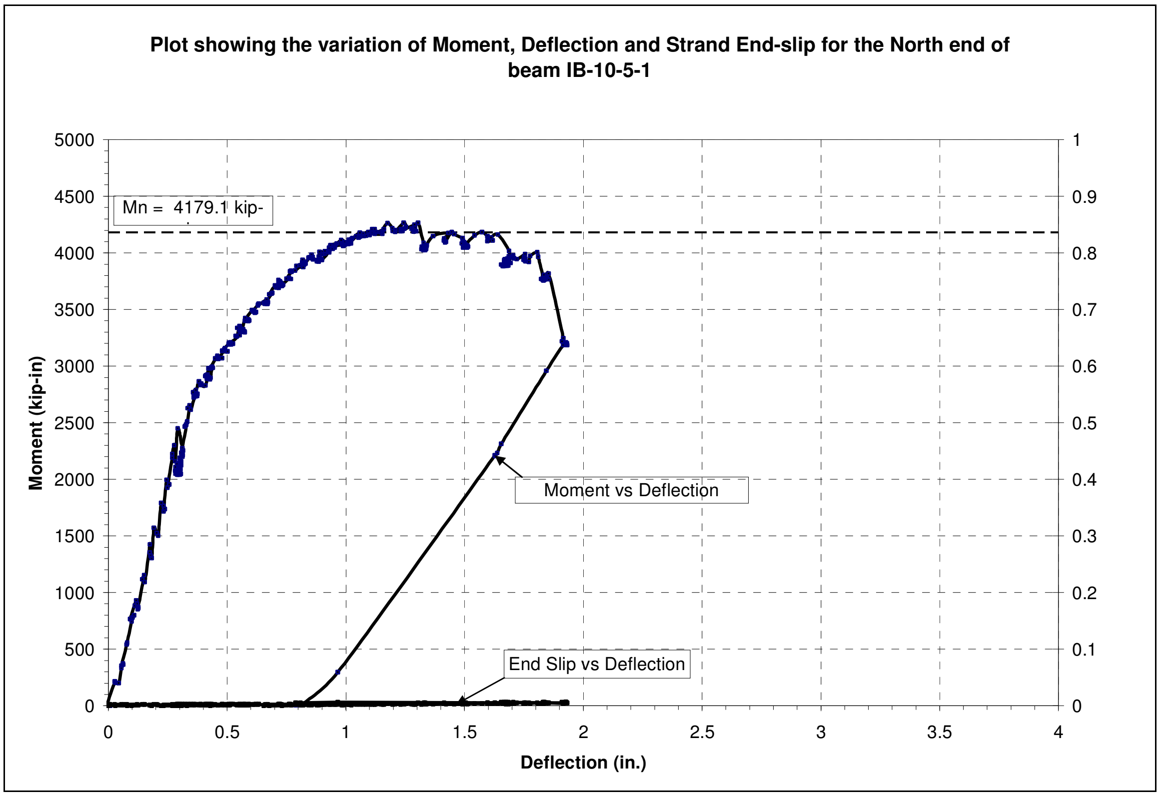
First flexural cracks occurred simultaneously with the first web shear cracks at the load of 77.2 kips (Shear = 51.5 kips) and deflection of 0.3 in. First flexural cracks occurred in a pair of cracks located approximately below the two load points. First web shear cracks occurred in the form of a number of cracks almost parallel to each other in the shear zone.

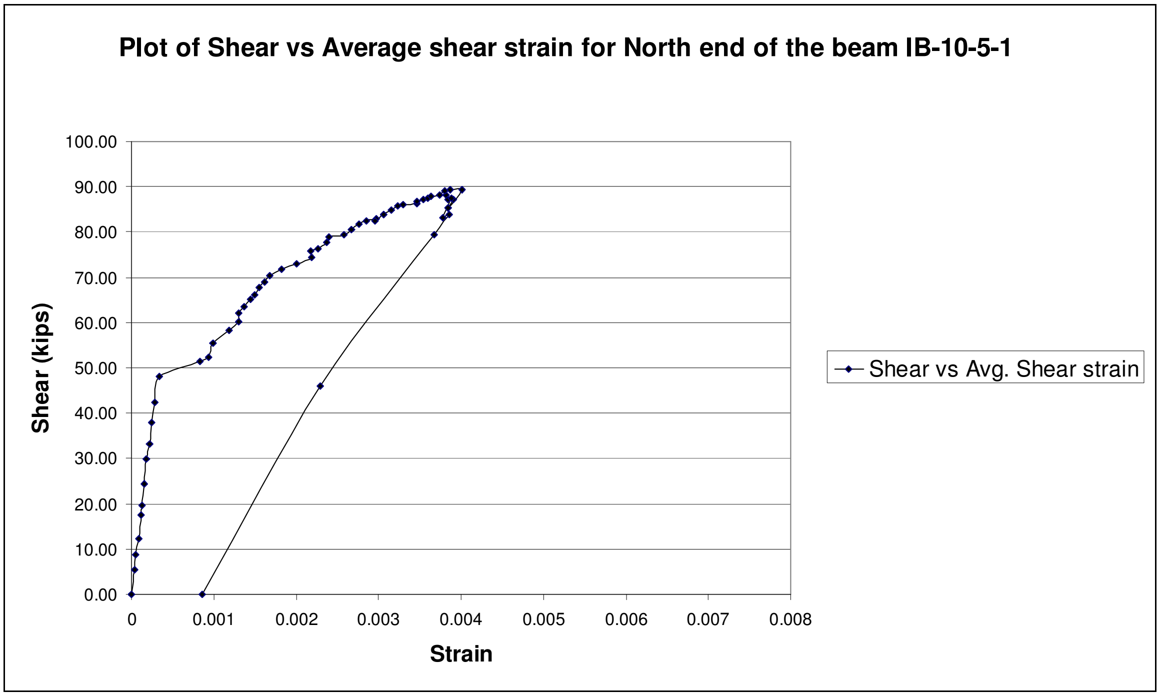
At the load of 90.4 kips (Shear = 60.3 kips) and deflection of 0.4 in. first secondary cracks were observed located at Stn. 64, 68 and 44 in. More and more secondary cracks occurred at further loadings along with occurrences of new flexural cracks.

All the cracks including first web-shear and first flexural cracks were clearly audible. Cracking sounds became prolonged after the load of 119.1 kips (Shear = 79.4 kips ; deflection = 0.9 in.)

An inclined flexural crack was observed with a loud sound near the South support at the load of 123.6 kips (Shear = 82.4 kips ; deflection = 1.0 in.). Values of load continued to increase with every increment up to the load of 133.8 kips (Shear = 89.2 kips ; deflection = 1.4 in.) where the load dropped suddenly with loud noise to 128.0 kips. Further loading increments resulted in recurring rise and fall of load values, every time with loud sounds. Finally it was decided to stop loading increments at the total deflection of 2.0 in. The beam did not reach its failure; however an inclined flexural crack towards the south side of the beam had grown wide and would have been the probable location of failure. Web-shear cracks were wide but not wide enough to suggest a shear failure of the beam.

End-slip readings stayed fairly at 0.00 in. until the load of 113.6 kips (Shear = 75.7 kips ; deflection = 0.8 in.) when the first end-slip of 0.01 in. was noticed. The end-slip reading went on increasing very gradually till the end of the test. Maximum end-slip noted was 0.03 in.)





(In all the photographs presented below, cracks marked in black represent the ones originated as flexural cracks while those marked in blue represent the web shear cracks. Red color was used only for marking the grid lines and station points. Numbers written in red should not be confused with the load values.)

Photo of the North end of the beam IB-10-5-1 showing the first web shear cracking incidentally the point of first flexural cracking as well)

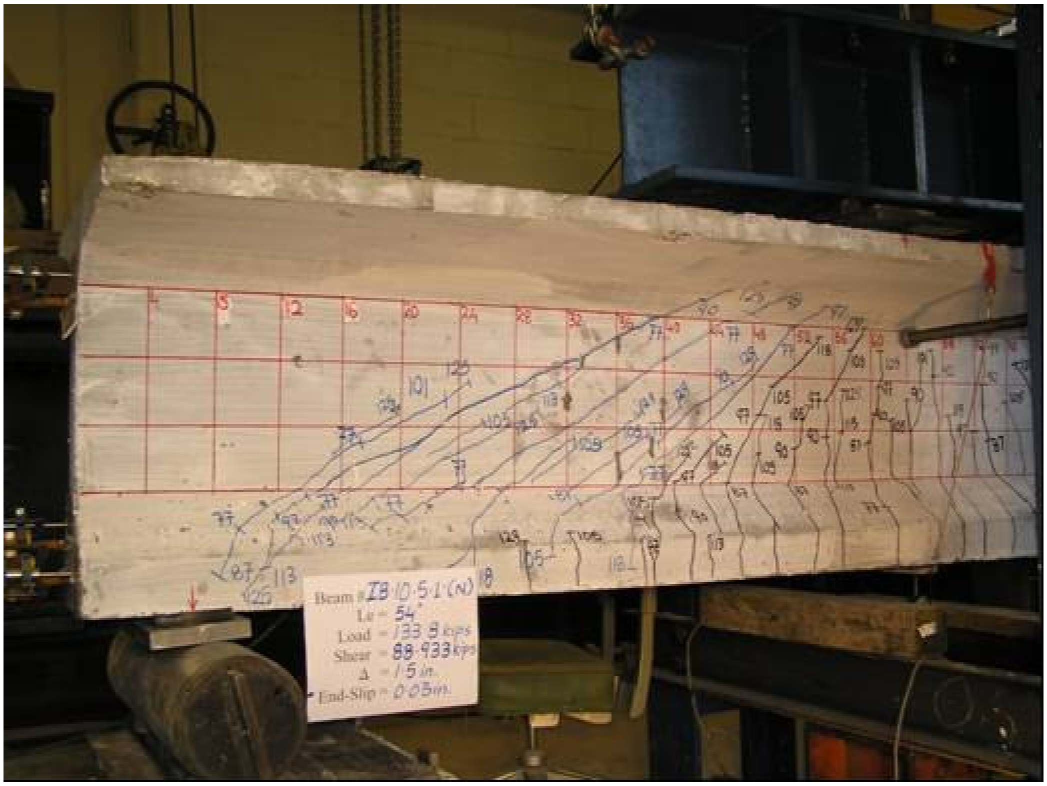


Photo of North end of beam IB-10-5-1 showing the cracking pattern at the maximum load

BEAM NAME: IB-10-5-1
END: SOUTH
DATE: 09/13/2005

TEST PARAMETERS	
Concrete Compressive Strength	**13490 psi**
Embedment Length(L_e)	**58 in.**
Span	**180 in.**
Failure Mode	**Failure did not occur**
Maximum Load	**121 kips**
Maximum Shear	**80.7 kips**
Maximum Moment	**4196.4 kip-in.**
Maximum Deflection attained	**1.55 in.**
Rebound after complete unloading	**1.2 in.**
Average NASP P.O value for strand "B"	**20.21 kips**

	Transfer lengths (in.) for beam # IB-10-5-1		
		At Release	At the time of testing
South	Top	-	21.7
	Middle	9.9	11.59
	Bottom East	12.45	30.14
	Bottom Central	12.45	10.25
	Bottom West	5.80	14.26

TEST SUMMARY

Load was applied in approximately 6.0 kips increments till first flexural cracking. Beyond this point the deflection was incremented by 0.025 in. till total deflection reached 1.30 in. Further increments of deflection were kept 0.05 in. DEMEC readings were taken at all load increments at both faces (East and West) with the rectangular rosette pattern at 36 in from the end being tested.

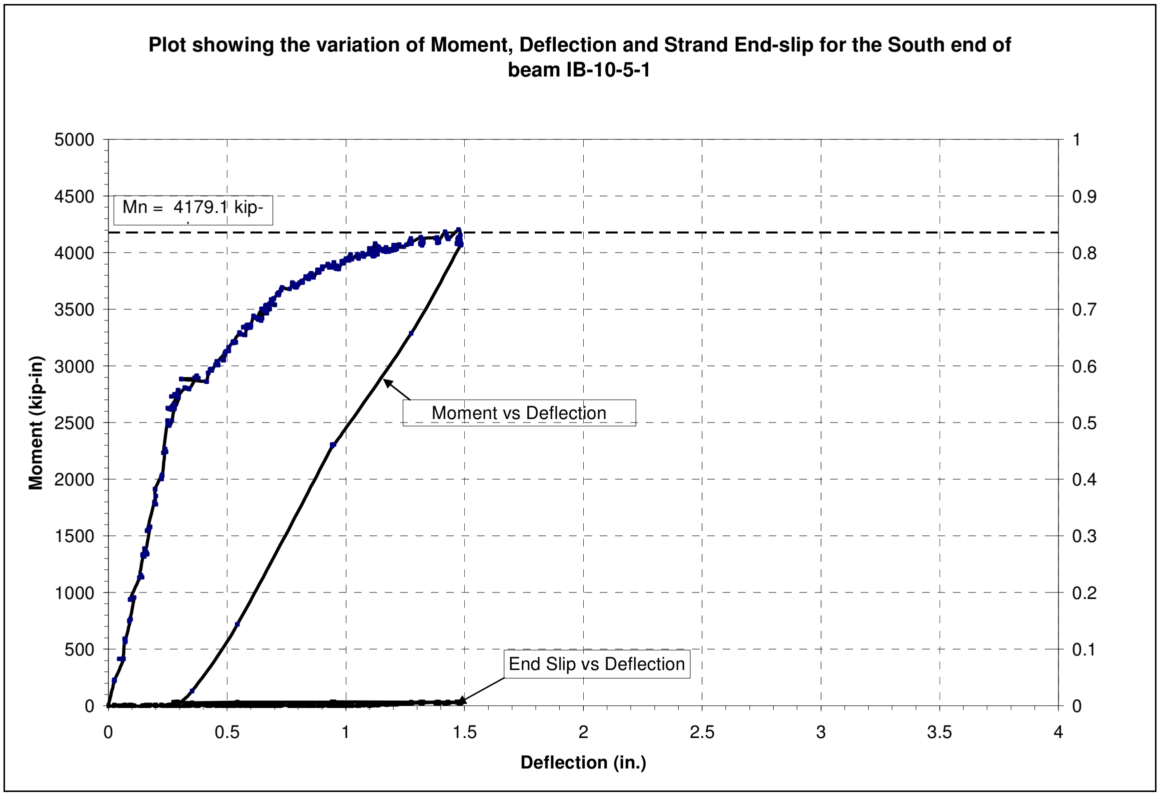
First flexural cracks occurred at 77.5 kips (Shear = 51.7 kips ; Deflection = 0.33 in.). These cracks occurred in the form of a pair of cracks located approximately below the two point loads. First web shear cracks followed immediately and were discovered at the load of 81 kips (Shear = 54 kips ; Deflection = 0.38 in.). First web shear cracks occurred in the form of a number of cracks almost parallel to each other in the shear zone. DEMEC readings were taken after cracking occurred.

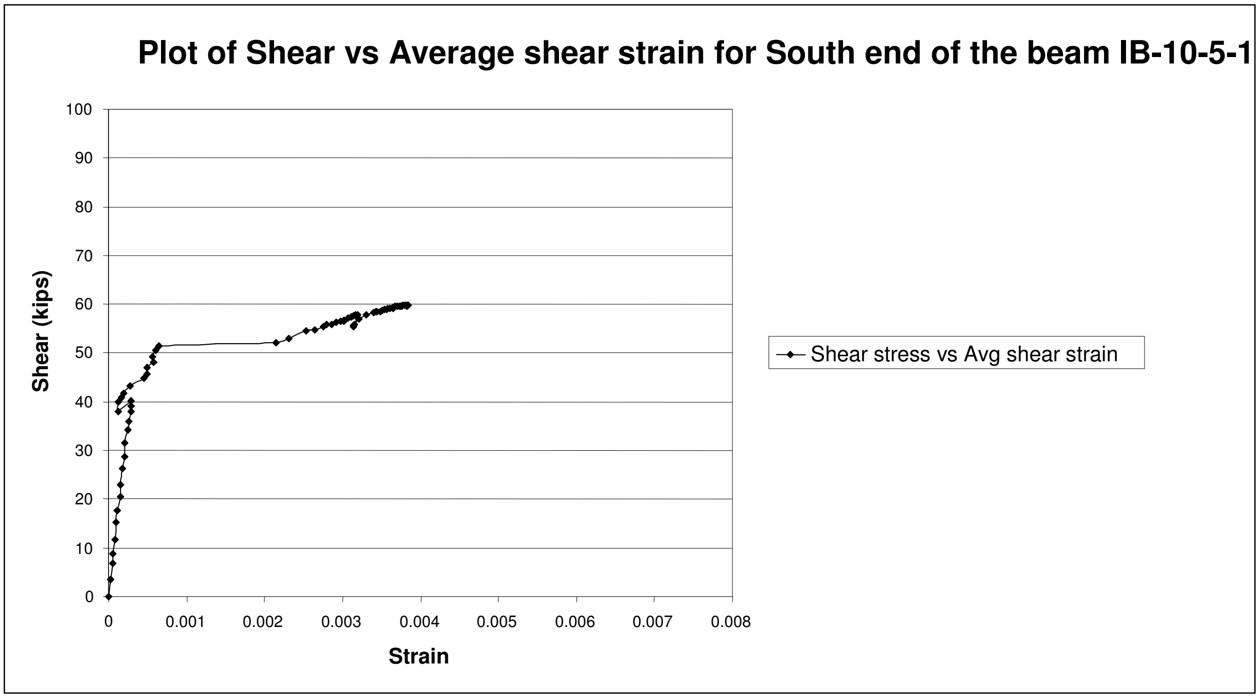
Between the first flexural and first web shear cracks a secondary crack was observed at Stn 68. More secondary cracks continued to occur throughout the loading cycle.

End-slip value remained at 0.00 in till the load reached 118 kips (Shear = 78.7 kips ; Deflection = 1.3 in.) where the first end-slip of 0.01 in. was noted. The value of end-slip stayed fairly constant at 0.01 in. till the maximum load was attained. With further increments, the end-slip very gradually rose and the maximum value was 0.02 in.

The value load went on increasing with every deflection increment till it reached 121 kips (Shear = 80.7 kips ; Deflection = 1.55 in.). At this point it was noticed that the flexural crack beyond Stn. 96 has grown in width. Web shear cracks were not wide enough to suggest a shear failure. Loading was stopped concluding that the beam was heading for a flexural concrete crushing failure.

DEMEC readings were taken at all load increments and after complete unloading. The end-slip value at the North end stayed 0.00 in throughout the loading and unloading cycle.





(In all the photographs presented below, cracks marked in black represent the ones originated as flexural cracks while those marked in blue represent the web shear cracks. Red color was used only for marking the grid lines and station points. Numbers written in red should not be confused with the load values.)

Photo of the South end of the beam IB-10-5-1 showing the first web shear cracking

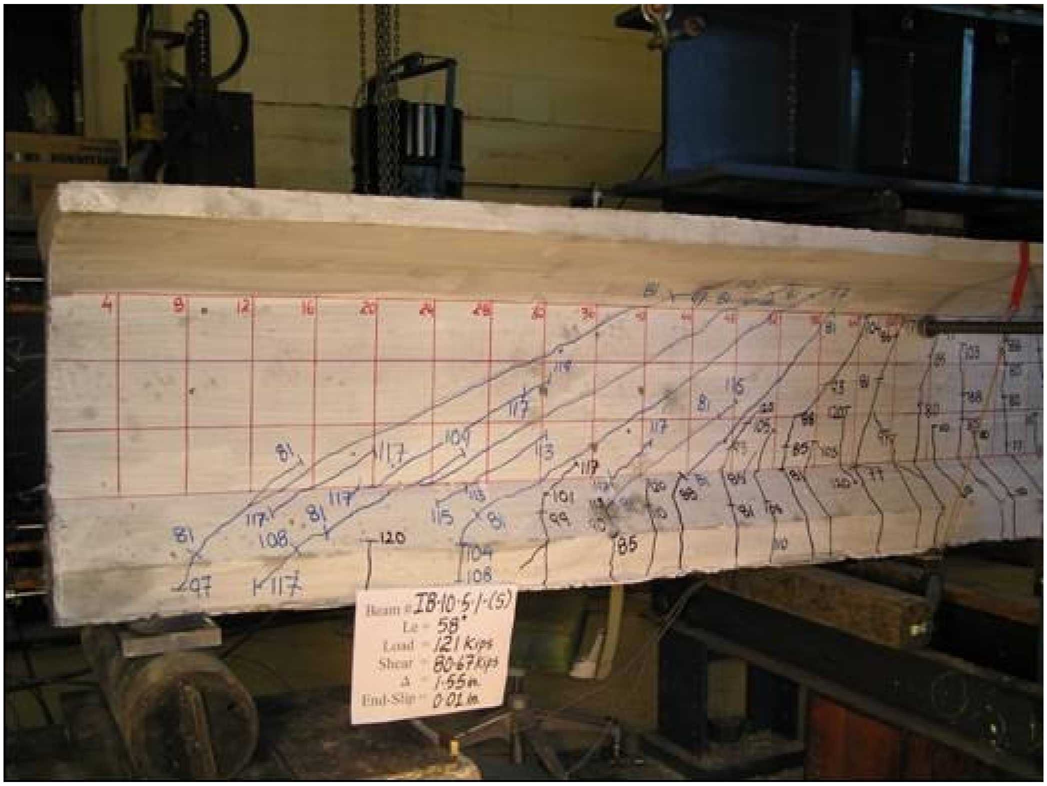


Photo of South end of beam IB-10-5-1 showing the cracking pattern at the maximum load

BEAM NAME: ID-6-5-1
END: NORTH
DATE: 09/19/2005

TEST PARAMETERS	
Concrete Compressive Strength	**9840 psi**
Embedment Length(L_e)	**72 in.**
Span	**222 in.**
Failure Mode	**Bond Failure**
Maximum Load	**80.4 kips**
Maximum Shear	**53.6 kips**
Maximum Moment	**3537.6 kip-in**
Maximum Deflection attained	**2.5 in.**
Rebound after complete unloading	**1.4 in.**
Average NASP P.O value for strand "D"	**6.89 kips**

	Transfer lengths (in.) for beam # ID-6-5-1		
		At Release	At the time of testing
North	Top	36.25	73.1
	Middle	28.96	36.99
	Bottom East	24.47	35.34
	Bottom Central	26.69	55.05
	Bottom West	23.47	32.71

<u>TEST SUMMARY</u>

Load was applied in approximately 4.0 kips increments till first flexural cracking. Beyond this point the deflection was incremented by 0.025 in. till total deflection reached 1.0 in. Further increments of deflection were kept 0.05 in. DEMEC readings were taken at all load increments at both faces (East and West) with the rectangular rosette pattern at 36 in. from the end being tested.

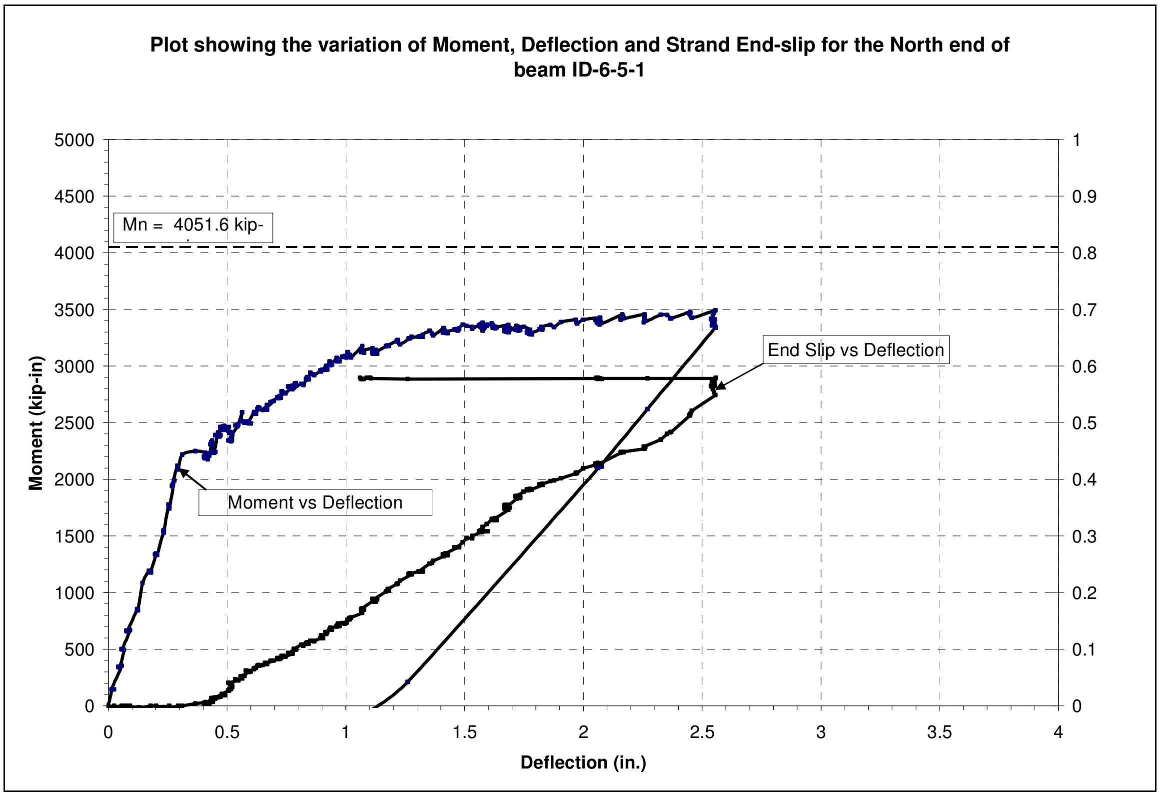
First flexural cracks were noticed at the load of 49 kips (Shear = 32.7 kips) and deflection of 0.3 in. First flexural cracks occurred in a pair of cracks located approximately below the two load points.

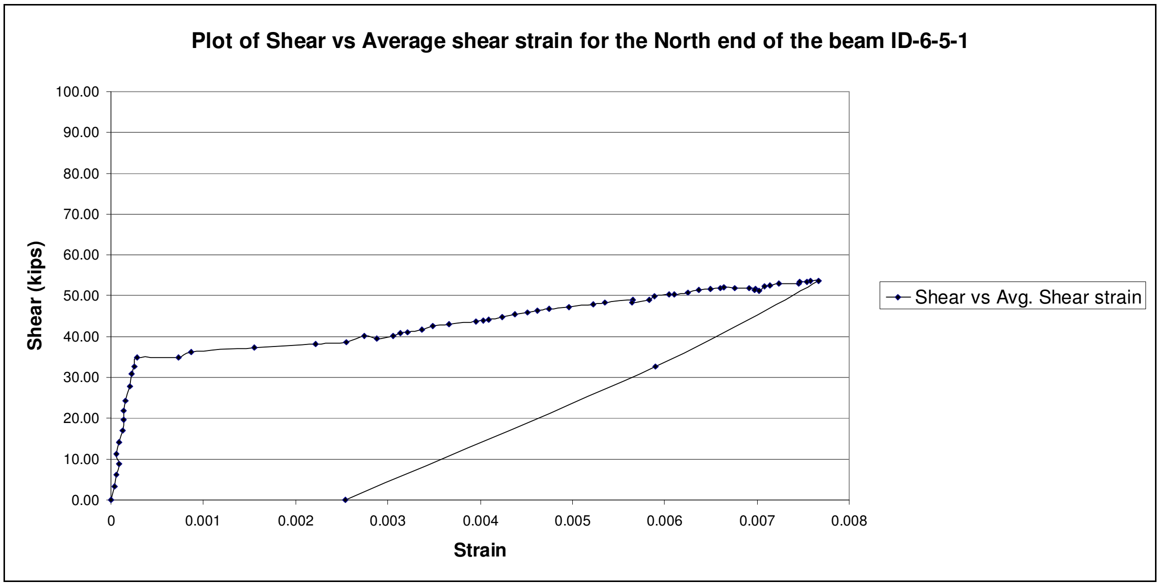
First web shear cracks were observed at the load of 52.4 kips (Shear = 34.9 kips ; Deflection = 0.35 in.) First web shear cracks occurred in the form of two cracks almost parallel to each other in the shear zone. The load dropped to 51.5 kips and the DEMEC points were taken at the reduced load i.e. after the cracks were completely formed.

An inclined flexural crack was observed at Stn.24 at the load of 54.2 kips (Shear = 36.1 kips; deflection = 0.38 in.). At the same time, first end slip of 0.01 in. was noticed. The load dropped to a value of 51.9 kips (Shear = 34.6 kips). End slip values went on increasing gradually at every further load increments.

The deflection increments were continued till the total end slip value reached 0.8 in. It was observed that the load remained fairly steady at around 80.4 kips while the deflection and end slip readings continued to increase at every increment.

End slip reading at the South end remained at 0.00 in. throughout the loading and unloading cycles.





(In all the photographs presented below, cracks marked in black represent the ones originated as flexural cracks while those marked in blue represent the web shear cracks. Red color was used only for marking the grid lines and station points. Number written in red should not be confused with the load values.)

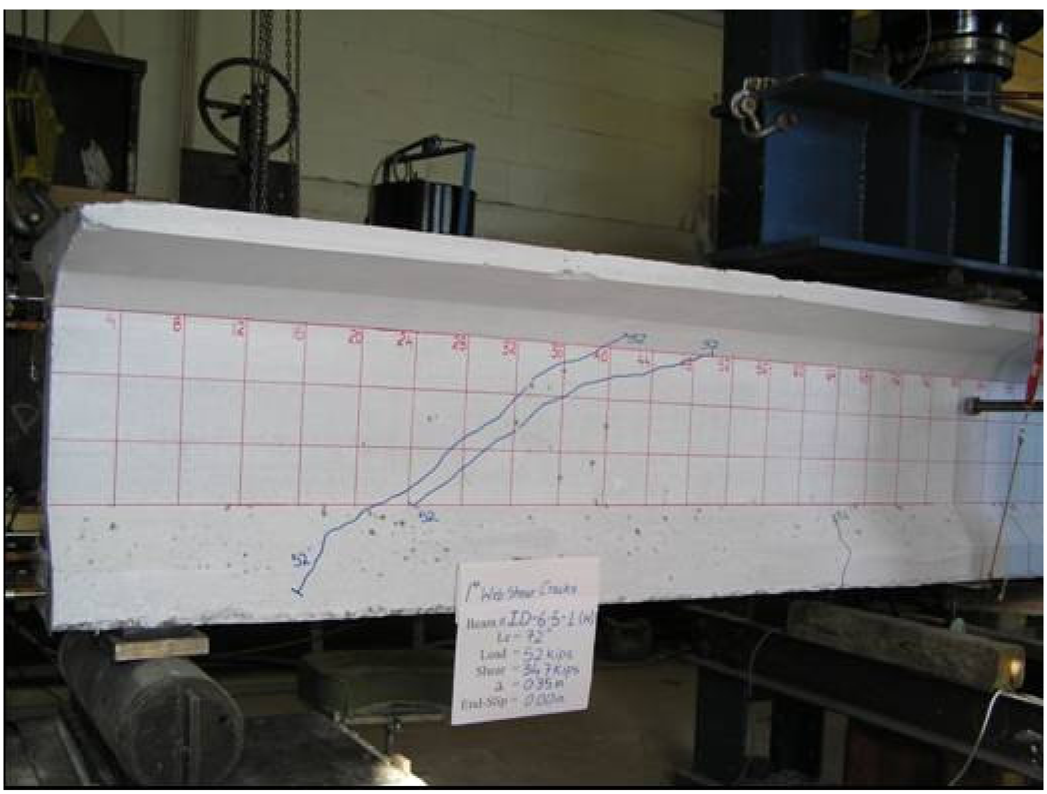


Photo of the North end of the beam ID-6-5-1 showing the first web shear cracking

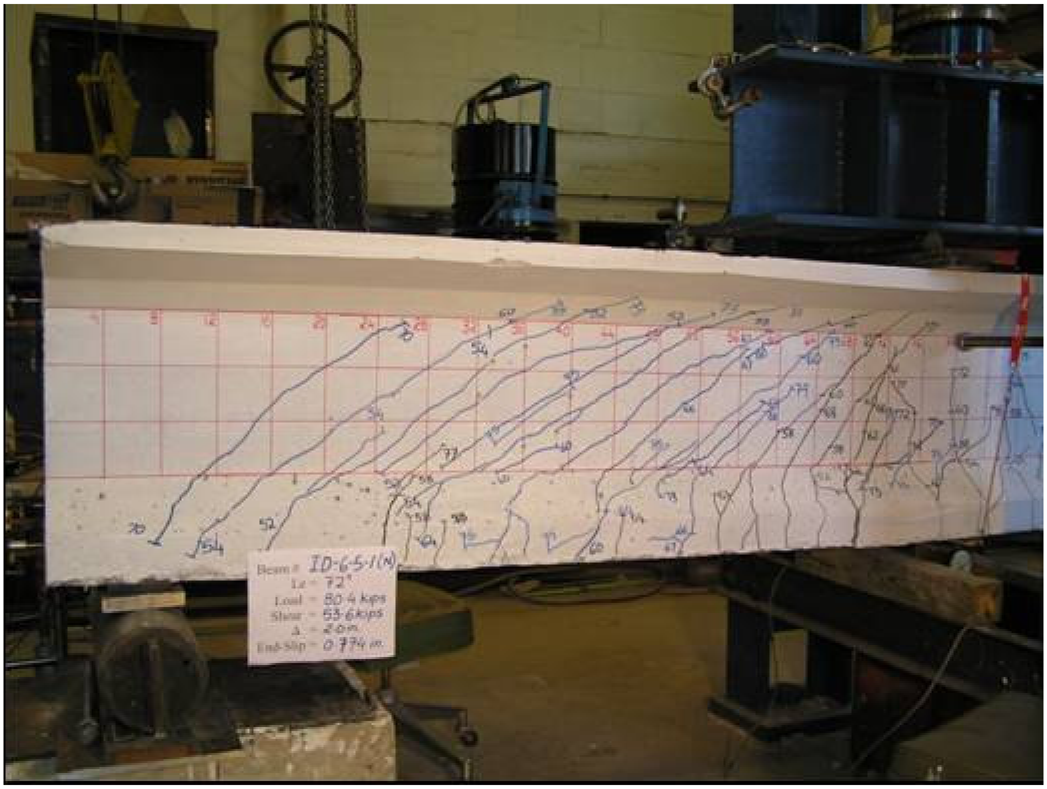


Photo of North end of beam ID-6-5-1 showing the cracking pattern at the maximum load

BEAM NAME: ID-6-5-1
END: SOUTH
DATE: 09/23/2005

TEST PARAMETERS	
Concrete Compressive Strength	**9840 psi**
Embedment Length(L_e)	**88 in.**
Span	**270 in.**
Failure Mode	**Bond**
Maximum Load	**60 kips**
Maximum Shear	**40 kips**
Maximum Moment	**3280 kip-in.**
Maximum Deflection attained	**3.5 in.**
Rebound after complete unloading	**2.0 in.**
Average NASP P.O value for strand "B"	**6.89 kips.**

	Transfer lengths (in.) for beam # ID-6-5-1		
		At Release	At the time of testing
South	Top	29.99	68.63
	Middle	11.04	26.67
	Bottom East	12.23	46.22
	Bottom Central	NA	NA
	Bottom West	2.56	9.1

TEST SUMMARY

North end test of the beam ID-6-5-1 resulted in total end-slip of 0.8 in. at the North end. To avoid any further end slip at the North end while the South end was tested, strands at the North end were being held in place with chucks as seen in the photo showing the arrangement for holding the strands.

Load was increased by 2.5 kips with every increment till the first flexural cracks were noticed. Beyond this point, the deflection was incremented by 0.025in. up to total deflection reached 1.1 in. and from this point up to total deflection of 1.8 in. increments were set to 0.05 in. Finally from this point till maximum deflection was reached, deflection was incremented by 0.1 in.

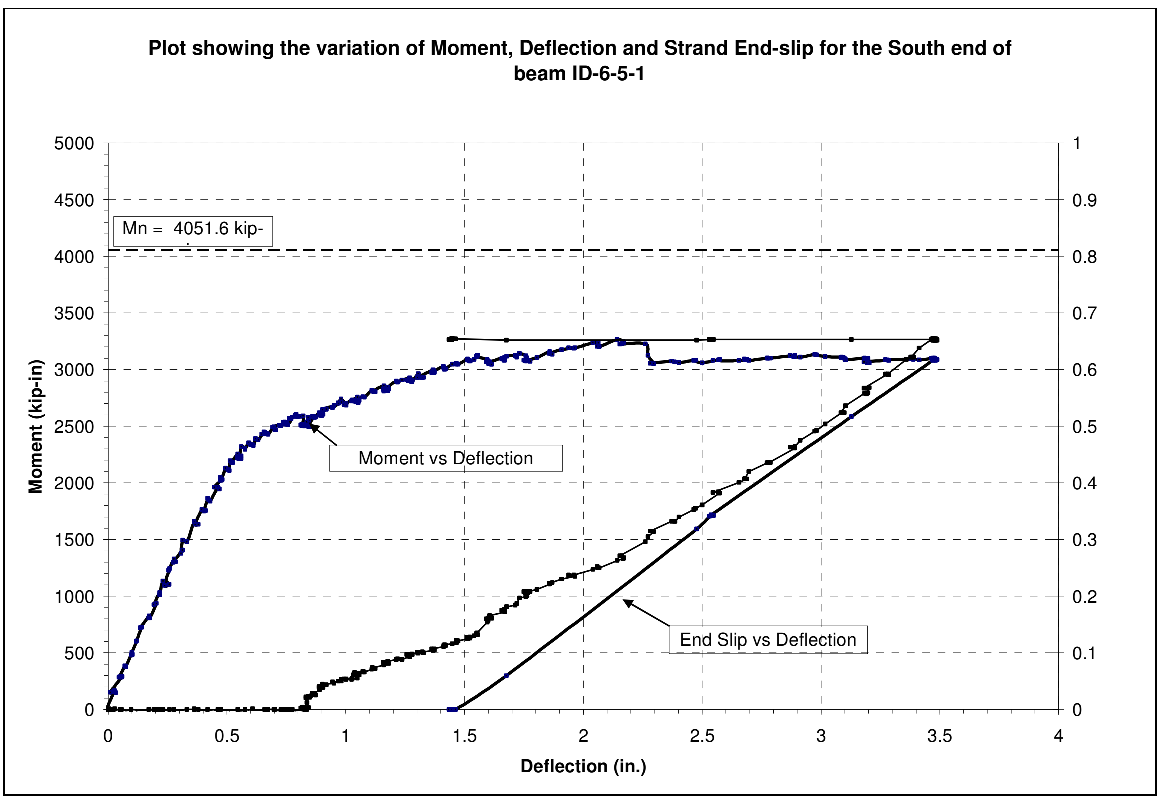
First flexural cracking was noticed at the load of 41.7 kips (Shear = 27.8 kips ; deflection = 0.58 in.). The first flexural cracking was in the form of a single crack formed approximately at the center of span. No significant drop of load was noticed at this point.

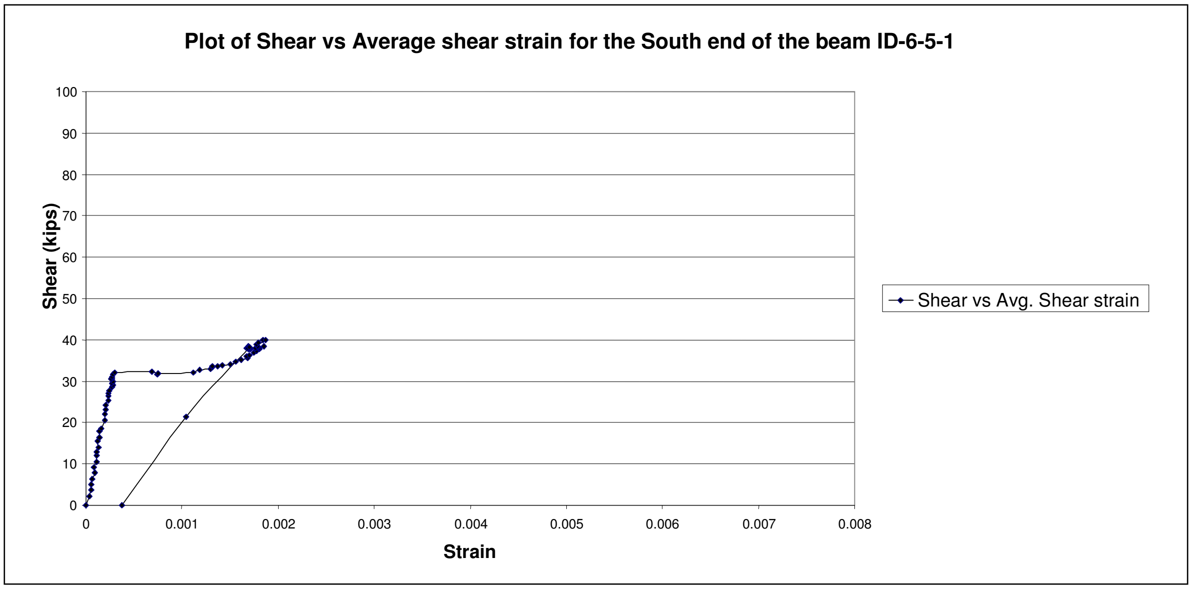
First web shear cracking was observed at the load of 48.6 kips (Shear = 32.4 kips ; deflection = 0.85 in.). First web shear cracks were in the form of a number of diagonal cracks fairly parallel to each other in the shear zone. Load value dropped to 45.8 kips at this stage. DEMEC readings were taken after the cracks were completely formed. First end slip of 0.01 in. was noticed at the East strand at this point.

As the load increased from 45.8 kips to 47.6 kips (Shear = 31.7 kips; deflection = 0.88 in.), first end slip of 0.01 in. the middle strand was observed. First inclined flexural cracks were noticed at Stn. 24 and Stn. 28. Along with these inclined flexural cracks, new shear cracks were formed at this load and the load value dropped further to 45.7 kips (Shear = 30.5 kips; deflection = 0.88 in.).The value of end slip went on increasing gradually with every load increment.

Maximum load attained was 60.0 kips (Shear = 40 kips; deflection at maximum load = 2.3 in.) when an audible crack was observed and the load decreased to 56.6 kips. The load value did not increase up to its apex value with further increments.

Deflection increments were stopped when the maximum end slip reached 0.75 in. (at the East strand) and maximum end slip of 0.74 in. at the middle strand.





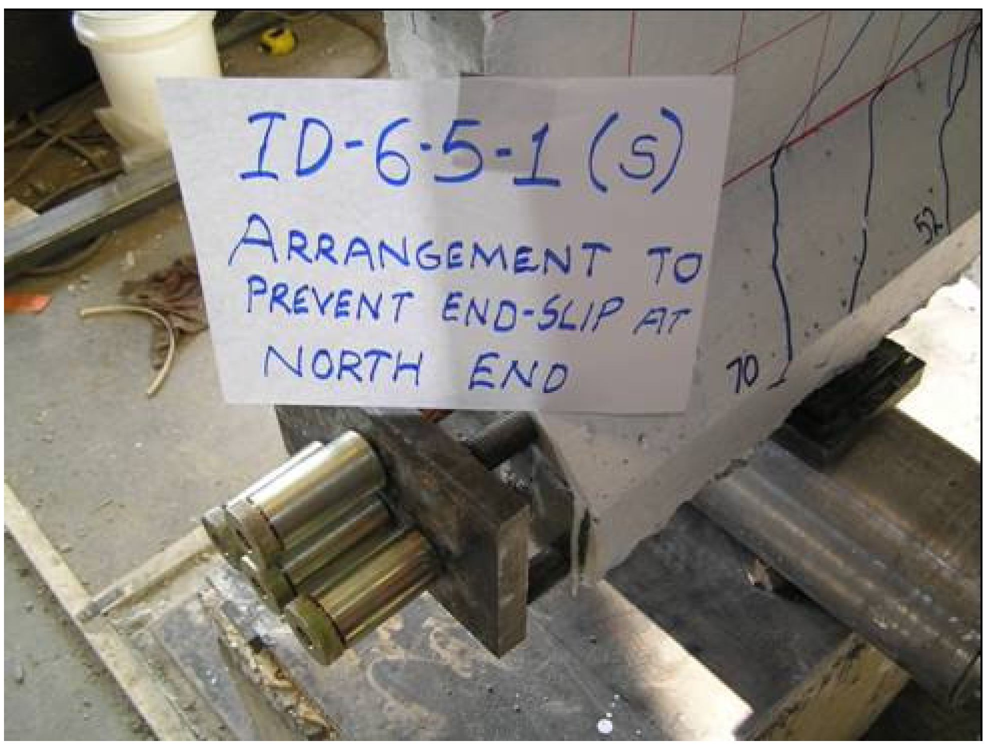


Photo showing chucks attached to strands to prevent any possible end slip.

(In all the photographs presented below, cracks marked in black represent the ones originated as flexural cracks while those marked in blue represent the web shear cracks. Red color was used only for marking the grid lines and station points. Number written in red should not be confused with the load values.)

Photo of the South end of the beam ID-6-5-1 showing the first web shear cracking

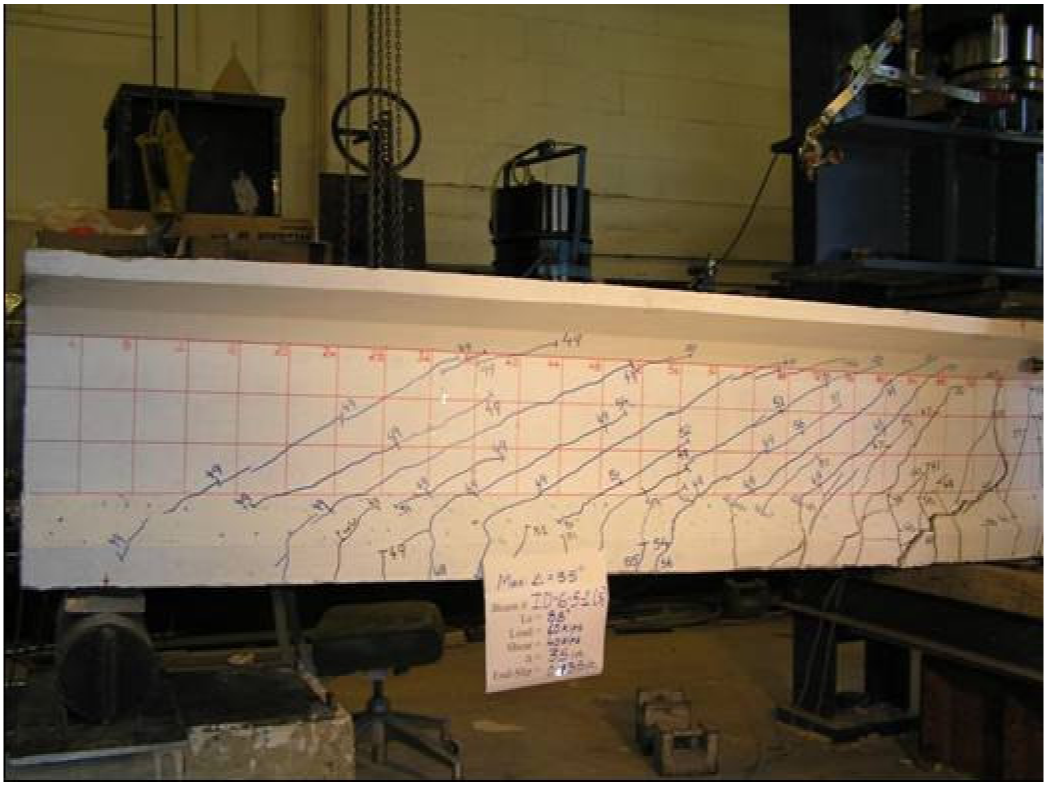


Photo of South end of beam ID-6-5-1 showing the cracking pattern at the maximum deflection

BEAM NAME: ID-10-5-1
END: NORTH
DATE: 09/30/2005

TEST PARAMETERS	
Concrete Compressive Strength	**14160 psi**
Embedment Length(L_e)	**88 in.**
Span	**270 in.**
Failure Mode	**Failure did not occur**
Maximum Load	**73.6 kips**
Maximum Shear	**49.1 kips**
Maximum Moment	**4026.2 kip-in**
Maximum Deflection attained	**5.2 in.**
Rebound after complete unloading	**2.9 in.**
Average NASP P.O value for strand "D"	**60.89 kips**

	Transfer lengths (in.) for beam # ID-10-5-1		
		At Release	At the time of testing
North	Top	NA	NA
	Middle	23.51	41.86
	Bottom East	19.03	29.63
	Bottom Central	15.99	38.93
	Bottom West	23.51	40.4

<u>TEST SUMMARY</u>

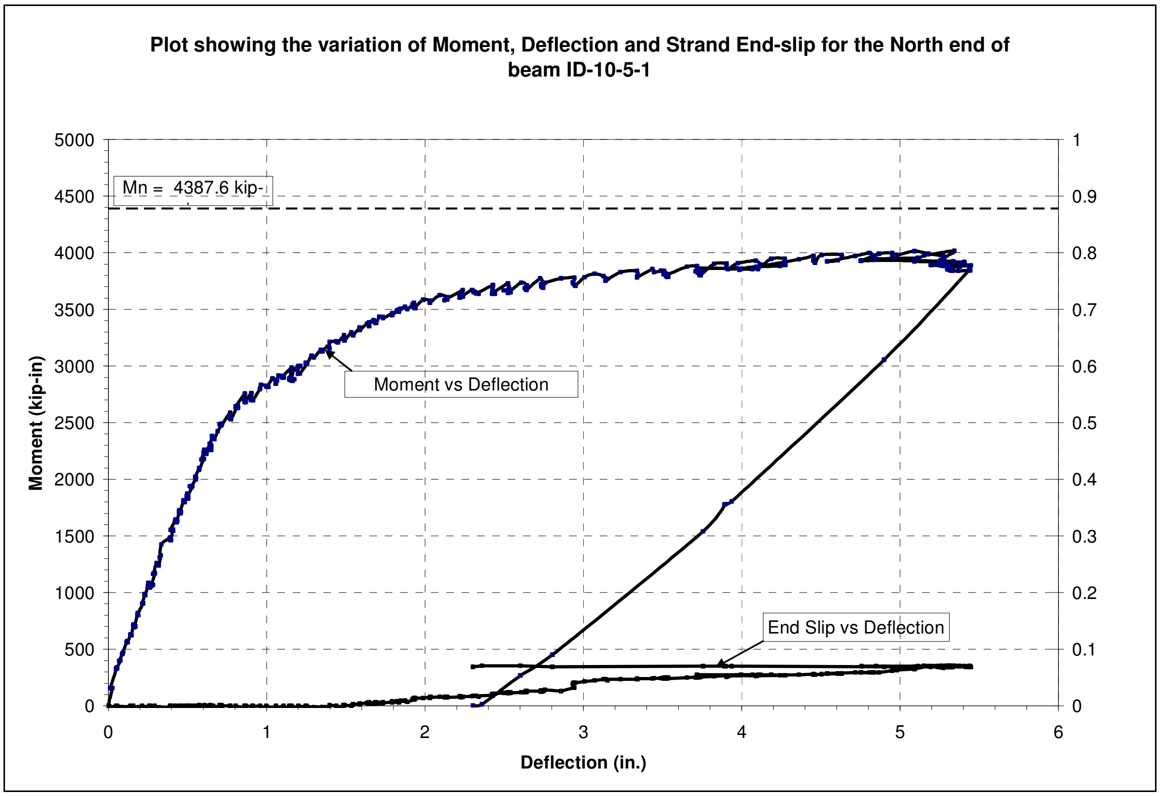
Strand end slip at the South end was prevented with the assembly of chucks as shown in the figure below.

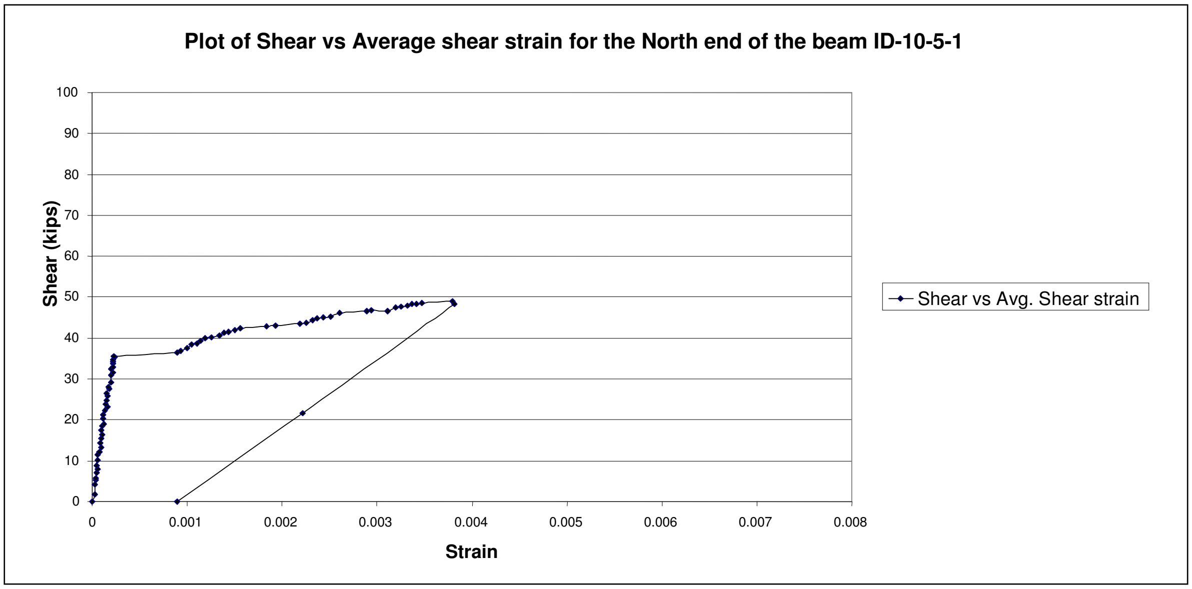
Load was applied in approximately 2.5 kips increments till first flexural cracking. Beyond this point the deflection was incremented by 0.025 in. till total deflection reached 0.7 in. Further increments of deflection were kept 0.05 in till total deflection of 2.0 in. Finally deflection was incremented by 0.1 in till maximum deflection was attained. DEMEC readings were taken at all load increments at both faces (East and West) with the rectangular rosette pattern at 36 in from the end being tested.

Since North end was tested after the South end, initially cracks were seen to propagate from the pre-existing cracks even before the first flexural cracks were noticed. First flexural cracks were observed at 48.7 kips (Shear = 32.5 kips; deflection = 0.85 in.) at Stn. 88, Stn. 92, Stn. 120. First secondary cracks followed at the load of 50.9 kips (Shear = 34 kips; deflection = 0.95 in.) and were formed at St. 104 and Stn.108. The load value dropped to 49.3 kips after the secondary cracks were formed.

First web shear cracking was noticed at 54.6 kips (Shear = 36.4 kips; deflection = 1.2 in.). The first web shear cracks occurred in the form of a number of diagonal cracks fairly parallel to each other in the shear zone. All cracks right from the first flexural cracks were clearly audible.

At 55.4 kips (Shear = 37 kips; deflection = 1.3 in.) first end slip of 0.01 was noticed on the middle strand. The value of end slip remained fairly constant at 0.01 in. till the last deflection increment. Deflection increments were stopped since the hydraulic ram reached its maximum stroke. Failure could not be attained, but from the values of load, deflection and end slip it was evident that the beam would fail in flexure.





(In all the photographs presented below, cracks marked in black represent the ones originated as flexural cracks while those marked in blue represent the web shear cracks. Red color was used only for marking the grid lines and station points. Number written in red should not be confused with the load values.)

Photo of the North end of the beam ID-10-5-1 showing the first web shear cracking

Photo of North end of beam ID-10-5-1 showing the cracking pattern at the maximum load

BEAM NAME: ID-10-5-1
END: SOUTH
DATE: 09/28/2005

TEST PARAMETERS	
Concrete Compressive Strength	**14160 psi**
Embedment Length(L_e)	**72 in.**
Span	**222 in.**
Failure Mode	**Bond**
Maximum Load	**91.8 kips**
Maximum Shear	**61.2 kips**
Maximum Moment	**4039 kip-in**
Maximum Deflection attained	**3.7 in.**
Rebound after complete unloading	**2.1 in.**
Average NASP P.O value for strand "D"	**6.89 kips**

	Transfer lengths (in.) for beam # ID-10-5-1		
		At Release	At the time of testing
South	Top	16.86	35.81
	Middle	23.94	53.04
	Bottom East	19.03	22.84
	Bottom Central	21.13	57
	Bottom West	23.61	30.73

TEST SUMMARY

Load was applied in approximately 5.0 kips increments till first flexural cracking. Beyond this point the deflection was incremented by 0.025 in. till total deflection reached 0.9 in. Further increments of deflection were kept 0.05 in. till total deflection of 2.0 in. Finally deflection was incremented by 0.1 in. till maximum deflection. DEMEC readings were taken at all load increments at both faces (East and West) with the rectangular rosette pattern at 36 in from the end being tested.

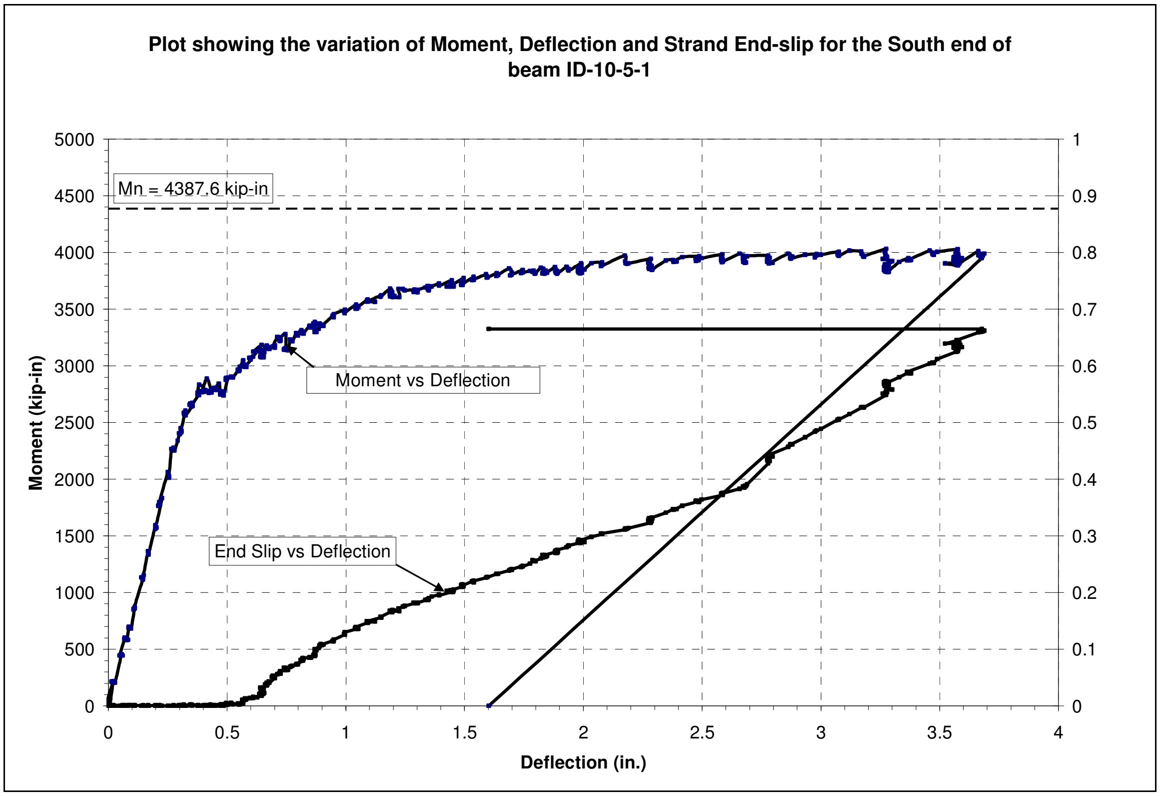
First flexural cracking was noticed at the load of 56.3 kips (Shear = 37.5 kips; deflection = 0.3 in.). Only a single crack was observed at this stage at the approximate midspan. First secondary crack was noticed at Stn. 88 at the load of 63.2 kips (Shear = 42.1 kips; deflection = 0.38 in.).

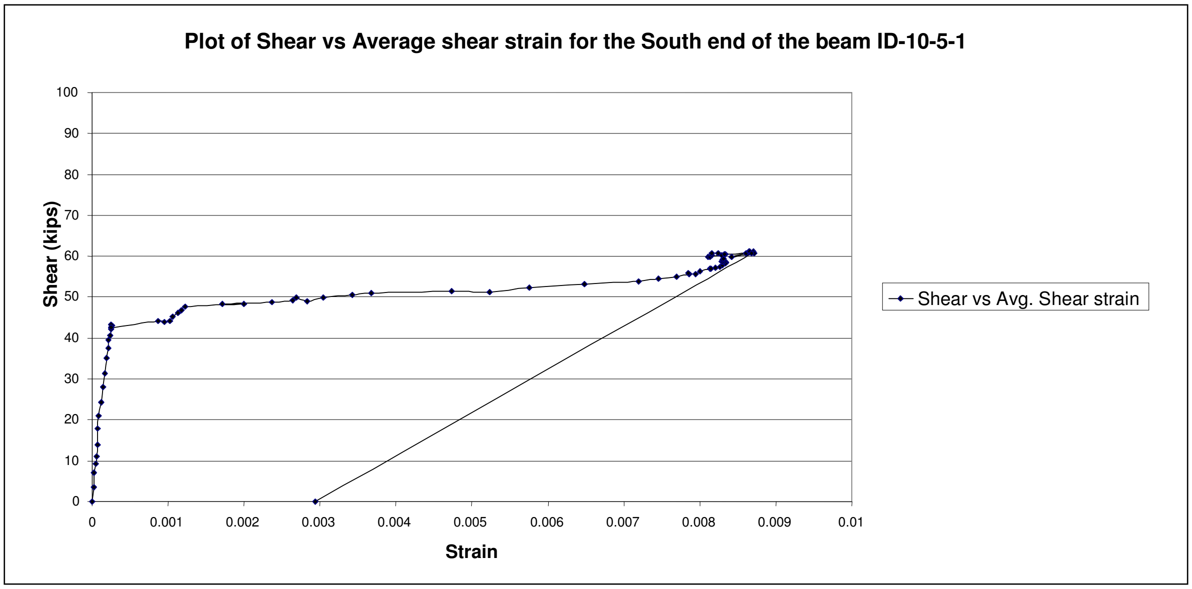
At the load of 66.3 kips (Shear = 44.2 kips; deflection = 0.48 in.) first web shear cracks were noticed and the value of load dropped to 62.4 kips. DEMEC readings were taken after the cracks were completely formed and at the lower value of load. First end slip of 0.01 in. was noticed when the load increased back to 66.3 kips at deflection = 0.53 in.

End slip values continued to increase throughout the loading cycle till it reached maximum value of 0.71 in. at the deflection of 3.7 in.

As it was observed that the load values were not increasing and with every increment only the end slip value was increasing, the loading was stopped as end slip value approached 3/4th in.

End slip values at the North end remained 0.00 in. throughout the loading cycle.





(In all the photographs presented below, cracks marked in black represent the ones originated as flexural cracks while those marked in blue represent the web shear cracks. Red color was used only for marking the grid lines and station points. Number written in red should not be confused with the load values.)

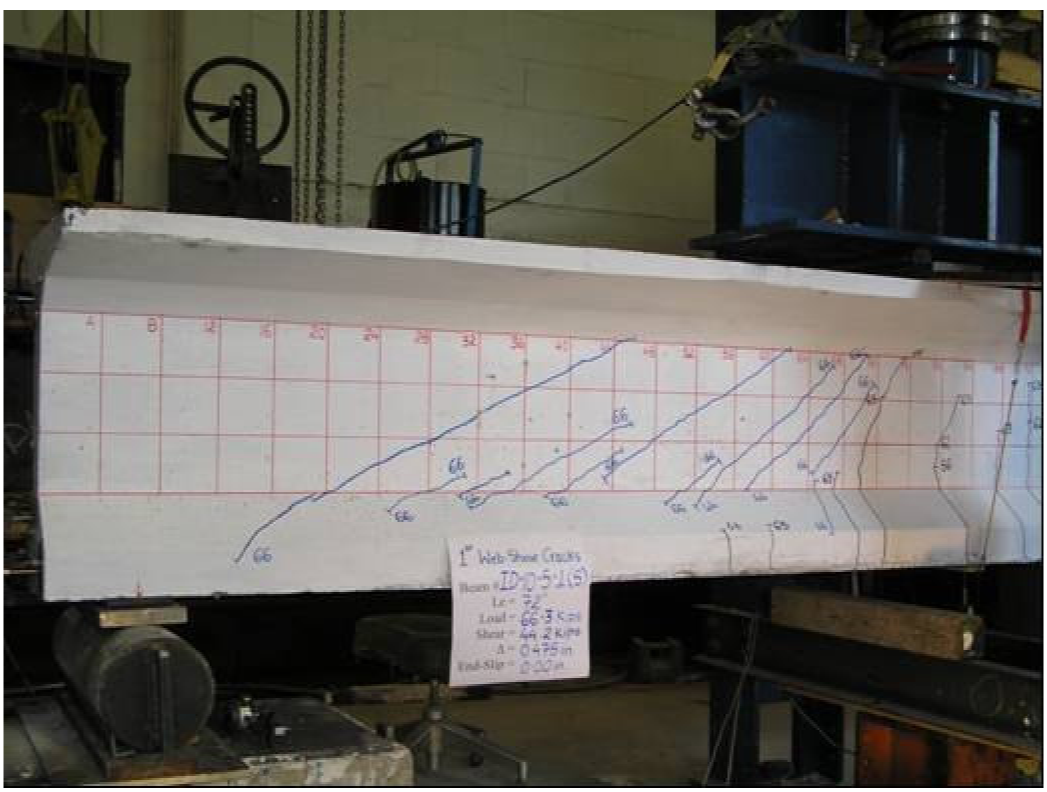


Photo of the South end of the beam ID-10-5-1 showing the first web shear cracking

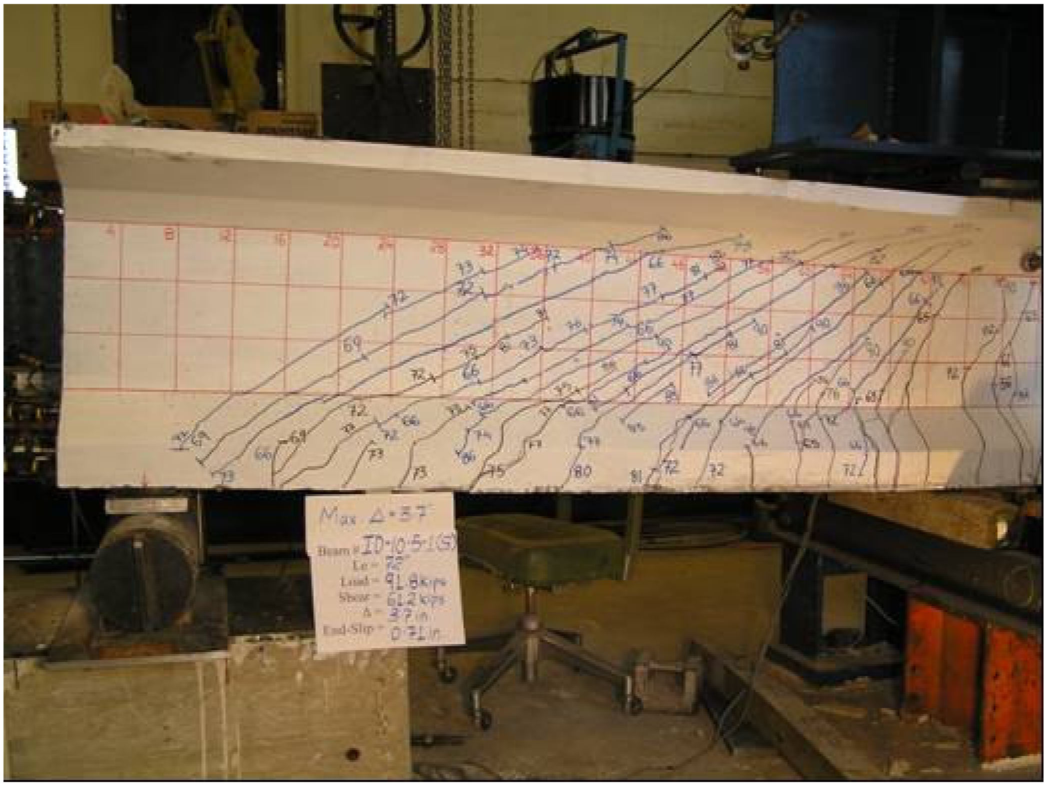


Photo of South end of beam ID-10-5-1 showing the cracking pattern at the maximum deflection

APPENDIX E

DEVELOPMENT LENGTH TEST SUMMARIES FOR I-SHAPED BEAMS WITH STRAND A (0.6 IN.)

BEAM NAME: IA-6-6-1
END: NORTH
DATE: 10/10/2005

TEST PARAMETERS	
Concrete Compressive Strength	**8990 psi**
Embedment Length(L_e)	**75 in.**
Span	**156 in.**
Failure Mode	**Shear failure at opposite side**
Maximum Load	**98.9 kips**
Maximum Shear	**49.5 kips**
Maximum Moment	**3267 kip-in**
Maximum Deflection attained	**1.65 in.**
Rebound after complete unloading	**0.5 in.**
Average NASP P.O value for strand "A"	**18.29 kips**

	Transfer lengths (in.) for beam # IA-6-6-1		
		At Release	At the time of testing
North	Top	22.84	NA
	Middle	-	NA
	Bottom East	18.36	NA
	Bottom Central	20.15	NA
	Bottom West	29.83	NA

TEST SUMMARY

The bottom surface of concrete at the North end was damaged during transportation and the strands were exposed. As a result, the support point was moved to 9 in. from the end instead of 6 in.

Photo showing the damage at the Bottom surface of North end of beam IA-6-6-1

Before starting the test, the web was reinforced with externally connected steel plates on both sides of the beam in the South shear span. Dimensions of the steel plates were 6in. x x1/4 in. and they extended from the South support up to the first loading point from the South end. Holes were drilled through the web to allow the plates to be bolted to the web along with being glued. The purpose of attaching these plates was to compensate for the horizontal shear reinforcement at the South end.

Load was applied in approximately 5.0 kips increments till first flexural cracking. Beyond this point the deflection was incremented by 0.025 in. till total deflection reached 1.0 in. Further increments of deflection were kept 0.05 in. DEMEC readings were taken at all load increments at both faces (East and West) with the rectangular rosette pattern at 39 in. from the end being tested (30 in. from the North support).

First web shear cracking was discovered at the load of 66.3 kips (Shear = 33.15 kips ; deflection = 0.33 in.). These cracks occurred in the form of two diagonal cracks in the shear zone. No flexural cracks were observed at this point.

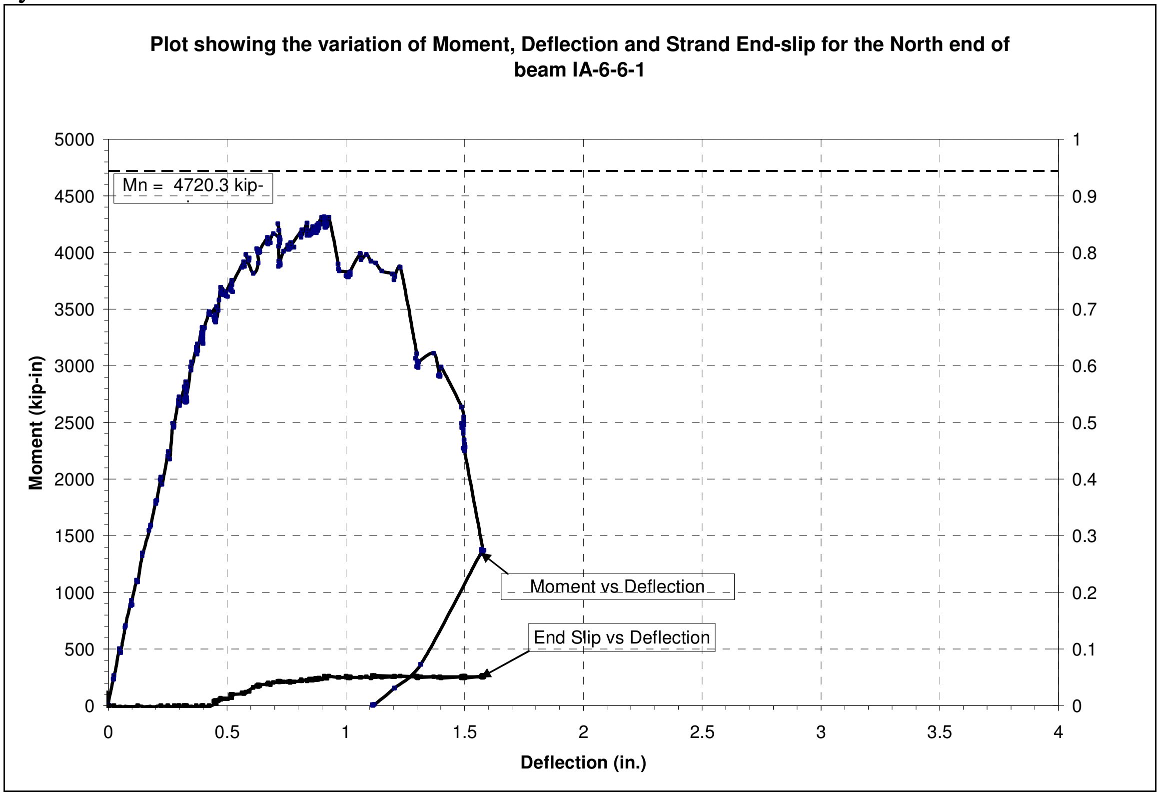
First flexural crack was noticed at the load of 73.3 kips (Shear = 36.7 kips; deflection = 0.38 in.) It occurred as a single crack at Stn. 80.

First end slip of 0.01 in. was observed at the load of 82.1 kips (Shear = 41.05 kips; deflection = 0.48 in.) Maximum value of end slip was 0.05 at failure.

As the load reached 98.9 kips (Shear = 49.5 kips; deflection = 1.0 in.), a sudden audible crack was noticed with the value of load dropping to 87 kips. The load value did not attain its maximum at any increment beyond this point. Finally as the deflection reached

1.65 in. shear failure was observed at the southern shear span in spite of attaching external steel reinforcement.

End slip reading at the South end remained 0.00 throughout the loading and unloading cycles.



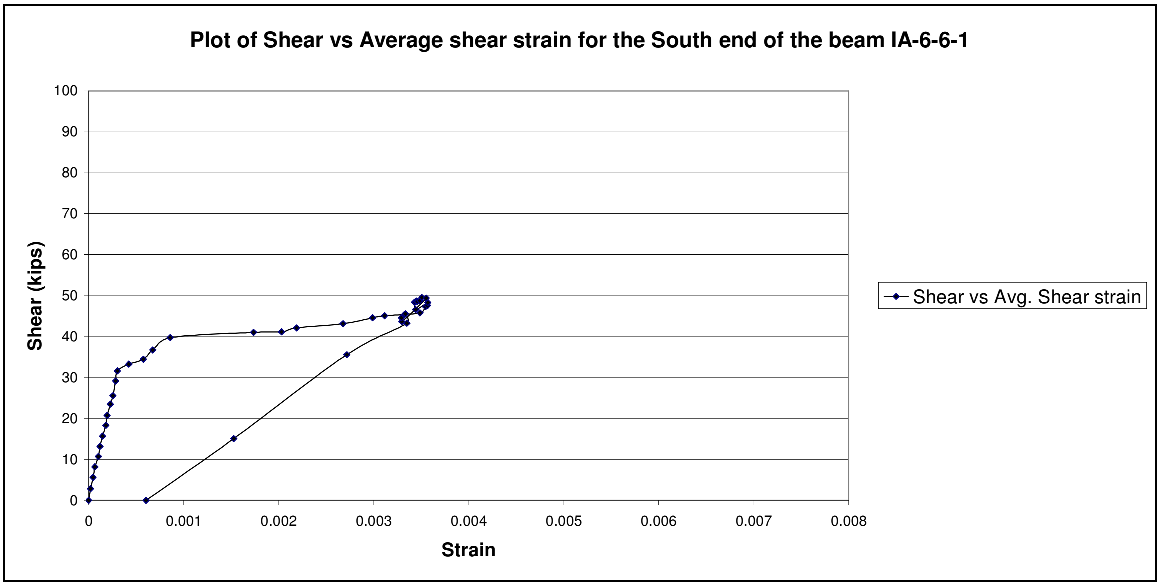


Photo showing the external steel plate attached on the web for compensating the horizontal reinforcement at the North end.

(In all the photographs presented below, cracks marked in black represent the ones originated as flexural cracks while those marked in blue represent the web shear cracks. Red color was used only for marking the grid lines and station points. Number written in red should not be confused with the load values.)

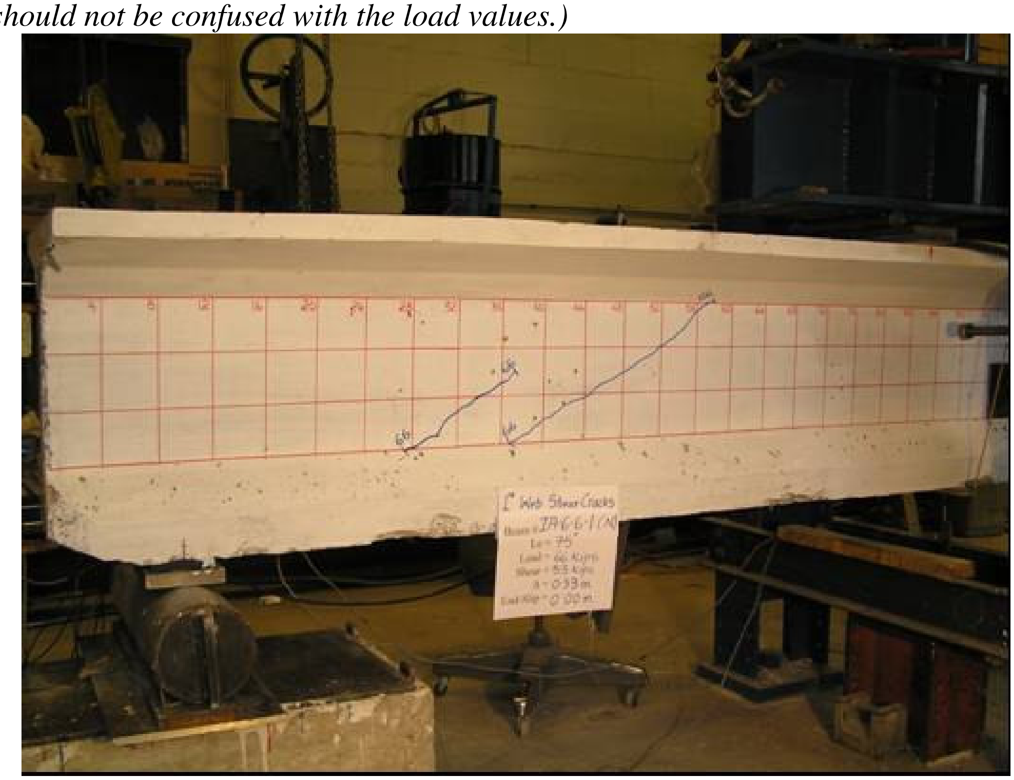


Photo of the North end of the beam IA-6-6-1 showing the first web shear cracking

Photo of South end of beam IA-6-6-1 showing the cracking pattern at the maximum load

BEAM NAME: IA-6-6-1
END: SOUTH
DATE: 10/10/2005

TEST PARAMETERS	
Concrete Compressive Strength	**8990 psi**
Embedment Length(L_e)	**91 in.**
Span	**188 in.**
Failure Mode	**Flexure**
Maximum Load	**107 kips**
Maximum Shear	**53.5 kips**
Maximum Moment	**4387 kip-in**
Maximum Deflection attained	**2.8 in.**
Average NASP P.O value for strand "A"	**18.29 kips**

	Transfer lengths (in.) for beam # IA-6-6-1		
		At Release	At the time of testing
South	Top	9.36	30.7
	Middle	-	
	Bottom East	16.33	36.72
	Bottom Central	20.15	
	Bottom West	22.21	

TEST SUMMARY

The bottom surface of concrete at the South end was damaged during transportation exposing the strands as seen in the photo below. The support p[oint was thus moved to 9 in. from the South end instead of 6 in.

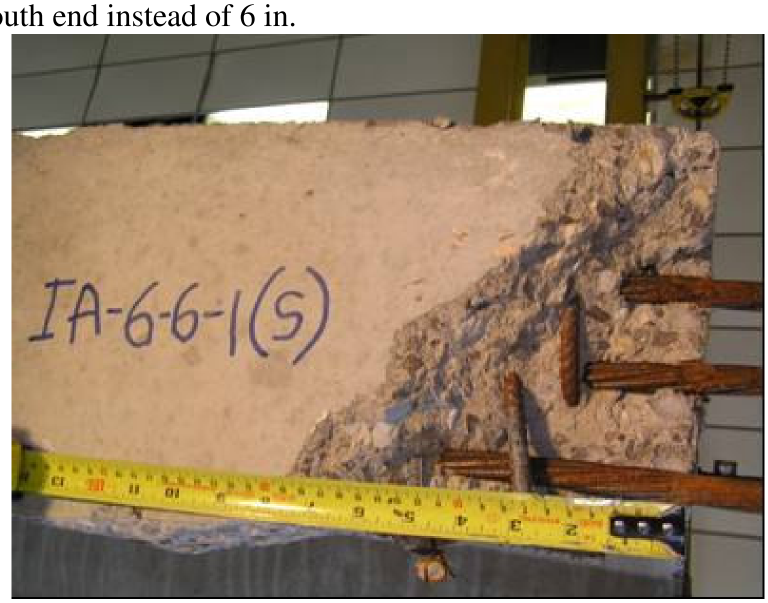


Photo showing the damage at South end caused during transportation

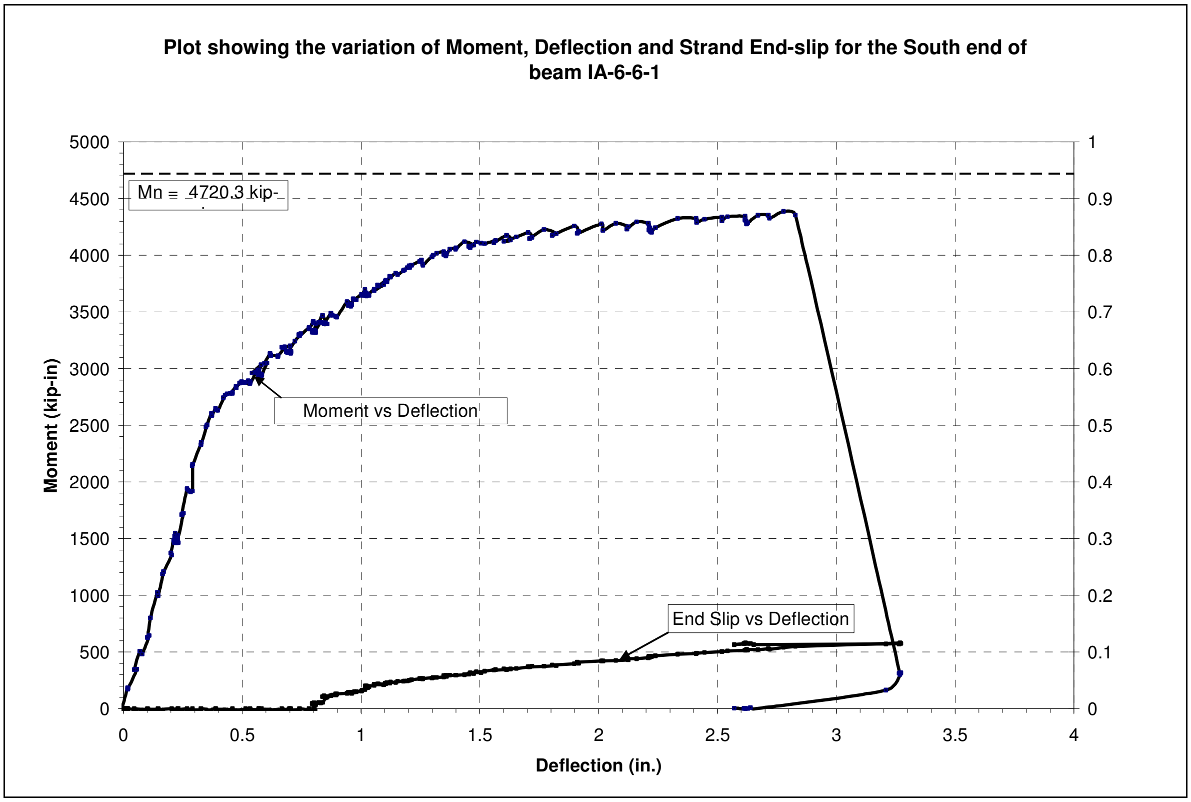
Load was applied in approximately 4.0 kips increments till first flexural cracking. Beyond this point the deflection was incremented by 0.025 in. till total deflection reached 1.2 in. Further increments of deflection were kept 0.05 in. Finally after the total deflection reached 1.7 in., the increments were set to 1.0 in. DEMEC readings were taken at all load increments at both faces (East and West) with the rectangular rosette pattern at 39 in. from the end being tested (30 in. from the South support).

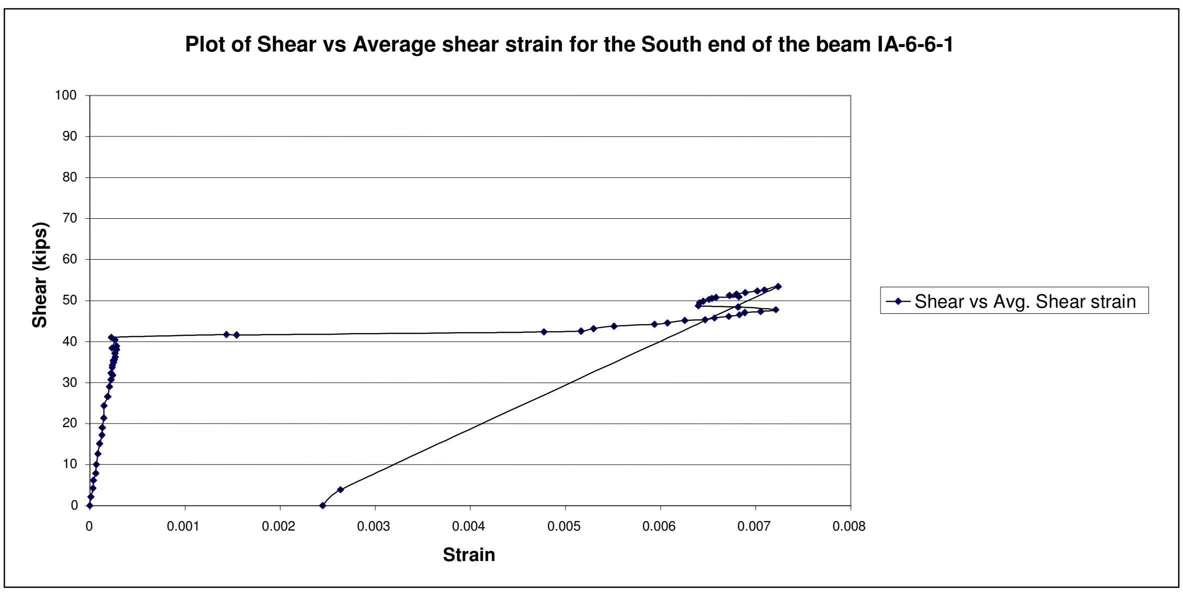
First flexural cracks were discovered at the load of 64.6 kips (Shear = 32.2 kips; deflection = 0.4 in.) First flexural cracks occurred in the form of three cracks symmetrically formed about the center span at Stn.88, Stn. 104 and Stn 112. No significant drop in load was noticed at this point.

First set of web shear cracks were noticed at the load of 79 kips (Shear = 39.5 kips; deflection = 0.7 in. Load value dropped to 76.8 kips immediately after the cracks were formed. DEMEC readings were taken at the reduced value of load.

First end slip of 0.01 in. was observed at the load of 83.5 kips (Shear = 41.6 kips; deflection = 0.8 in.) The value of end slip continued to increases with load till the point of flexural failure at the load of 107 kips (Shear = 53.5 kips ; deflection = 2.8 in.). Maximum end slip value recorded was 0.12 in.

End slip reading at the North end remained 0.00 throughout the loading and unloading cycles.





(In all the photographs presented below, cracks marked in black represent the ones originated as flexural cracks while those marked in blue represent the web shear cracks. Red color was used only for marking the grid lines and station points. Number written in red should not be confused with the load values.)

Photo of the South end of the beam IA-6-6-1 showing the first web shear cracking

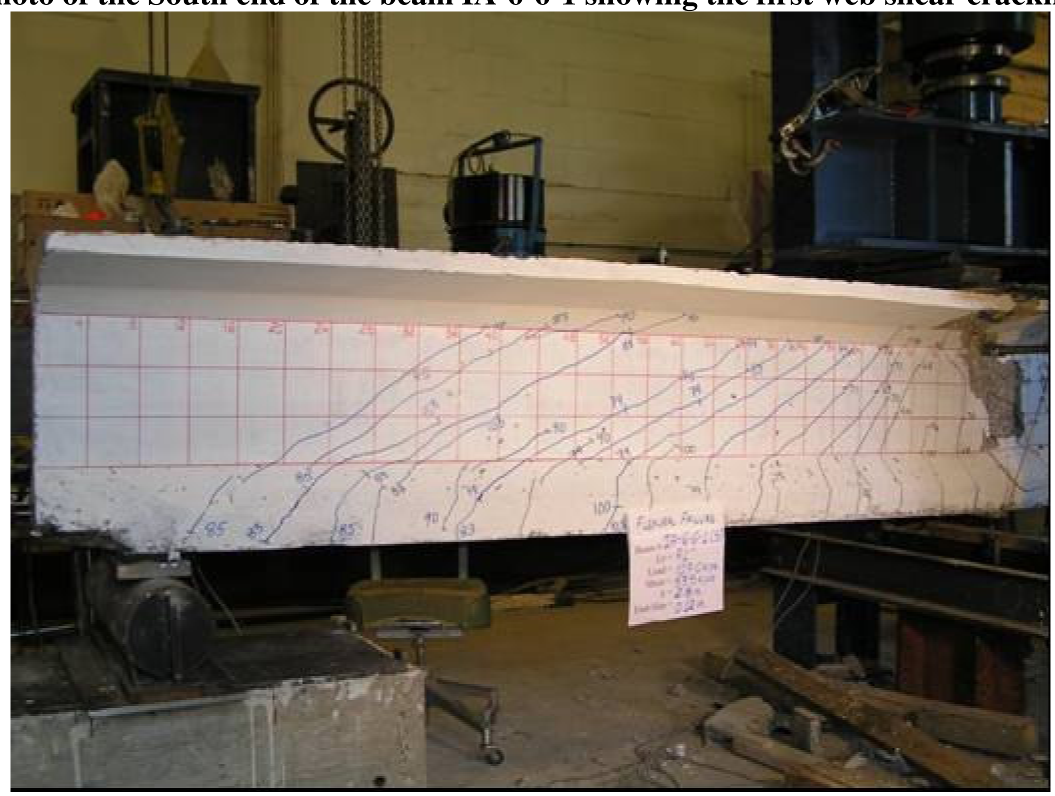


Photo of South end of beam IA-6-6-1 showing the cracking pattern at Flexural failure

BEAM NAME: IA-10-6-1
END: NORTH
DATE: 11/02/2005

TEST PARAMETERS	
Concrete Compressive Strength	**14990 psi**
Embedment Length(L_e)	**58 in.**
Span	**166 in.**
Failure Mode	**Shear failure at the opposite end**
Maximum Load	**127 kips**
Maximum Shear	**81.6 kips**
Maximum Moment	**4243.2 kip-in**
Maximum Deflection attained	**1.2 in.**
Average Transfer Length (L_t) @ release	**-**
@ time of testing	**-**
Average NASP P.O value for strand "A"	**18.29 kips**

TEST SUMMARY

Before starting the test the strands on the South end were fixed with chucks for preventing any end slip from that end as the South end was already tested.

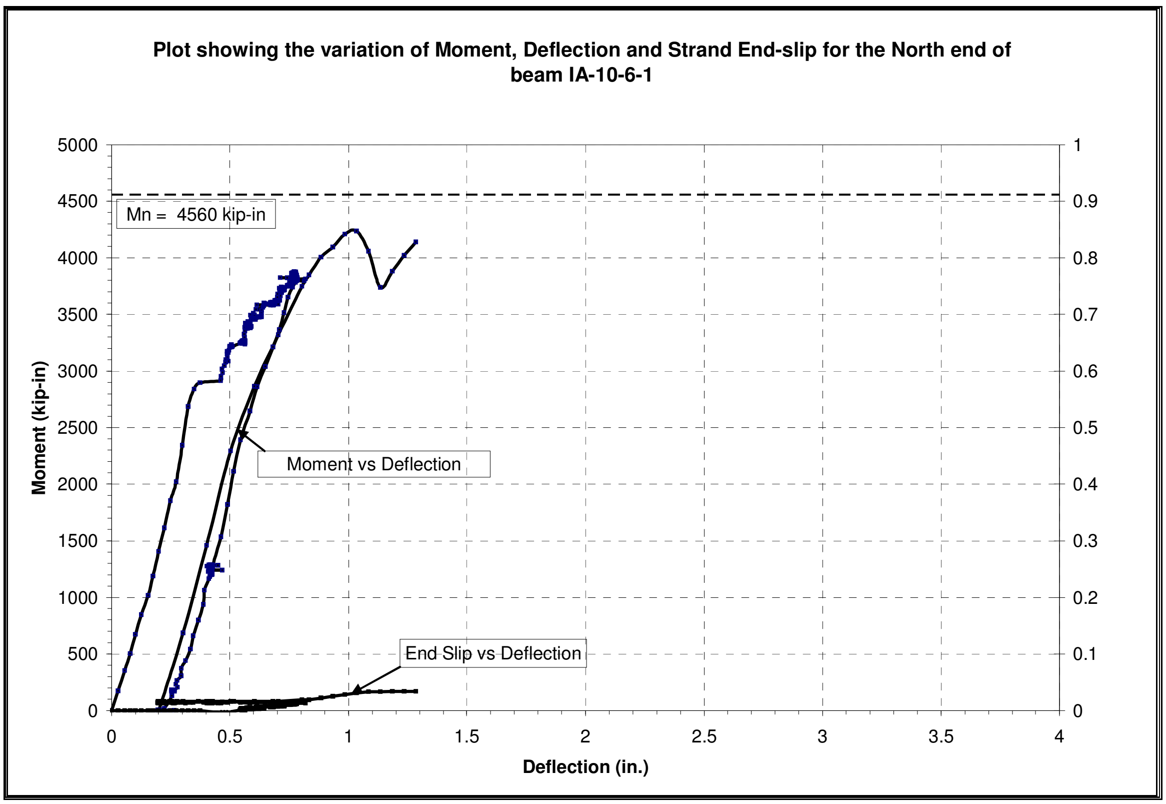
Photo showing chuck assembly at South end

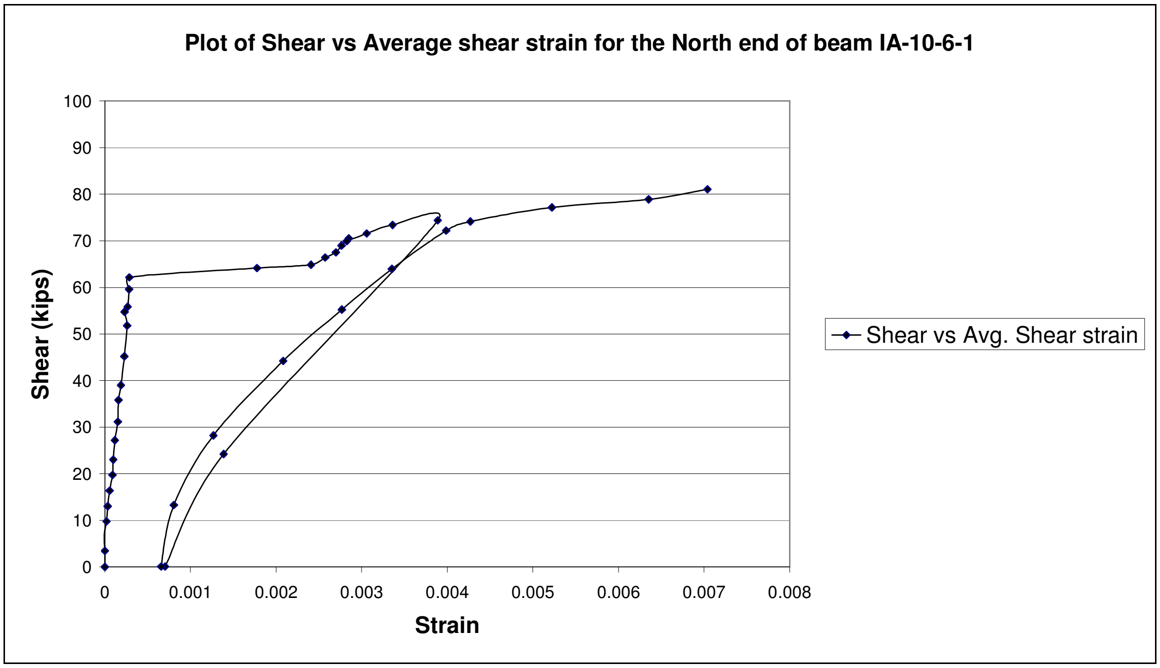
The beam was loaded in two loading cycles. For the first loading cycle, load was applied in approximately 5.0 kips increments till the total defection reached 0.7 in. The beam was unloaded completely at this stage. For the second loading cycle, deflection was incremented by approximately 0.1 in. till earlier value was attained. Beyond this, the deflection increments were set to 0.05 in. till the end of the test. New cracks which occurred during the second loading were marked with a bar on top of the load values at which they occurred. DEMEC readings were taken at all load increments at both faces (East and West) with the rectangular rosette pattern at 36 in from the end being tested.

First flexural crack was observed simultaneously with the first web shear cracking at the load of 85.2 kips (Shear = 54.8 kips; deflection = 0.35 in.) No significant drop in load was noticed.

First end slip of 0.01 in was observed at the load of 100.9 kips (Shear = 64.9 kips; deflection = 0.45 in.) End slip reading went on increasing very slowly till at failure, the maximum noted end slip reading was 0.05 in.

It was noticed that the shear cracks were growing wider in the South side shear zone. Finally the beam gave off violently at the maximum load of 127 kips (Shear = 81.6 kips; deflection = 1.2 in.) The shear failure of beam at the opposite side was extremely violent with the beam literally breaking into two halves. Unloading data for the beam could not be noted due to the nature of beam failure.





(In all the photographs presented below, cracks marked in black represent the ones originated as flexural cracks while those marked in blue represent the web shear cracks. Red color was used only for marking the grid lines and station points. Number written in red should not be confused with the load values.)

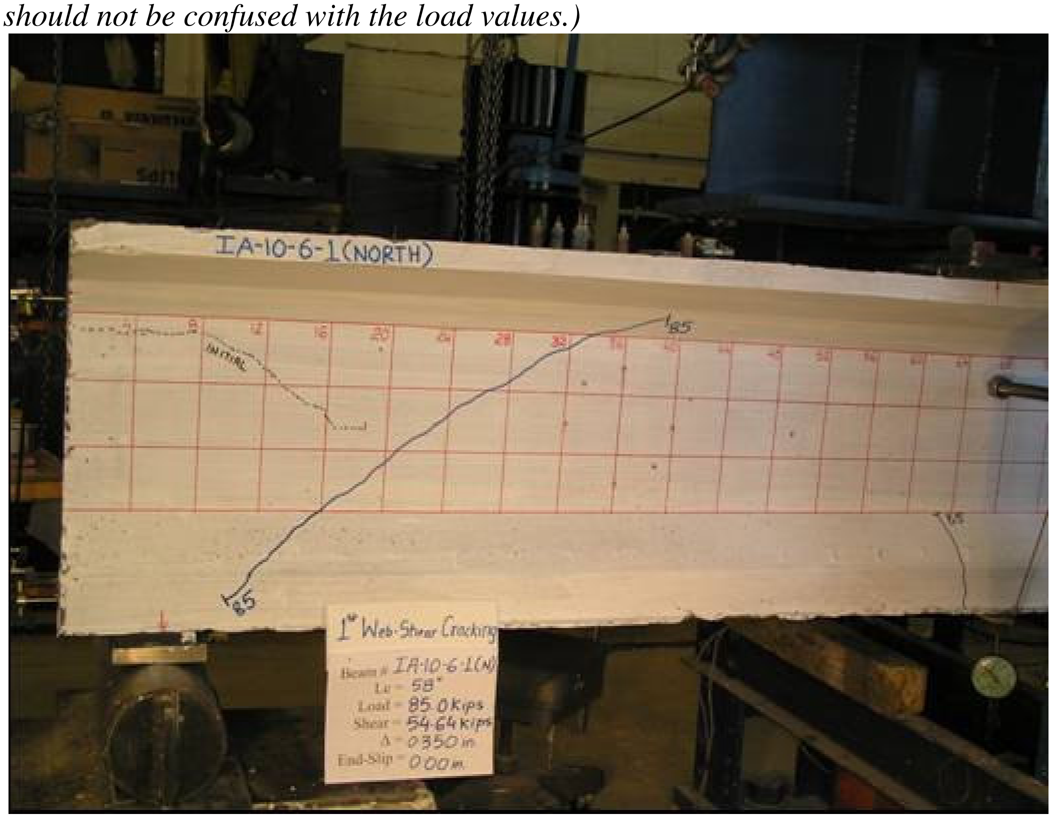


Photo showing first web shear cracking for IA-10-6-1-N

Photo showing shear failure at the opposite end for IA-10-6-1-N

BEAM NAME: IA-10-6-1
END: SOUTH
DATE: 10/26/2005

TEST PARAMETERS	
Concrete Compressive Strength	**14990 psi**
Embedment Length(L_e)	**72 in.**
Span	**222 in.**
Failure Mode	**Strand Fracture**
Maximum Load	**105 kips**
Maximum Shear	**70 kips**
Maximum Moment	**4620 kip-in.**
Maximum Deflection attained	**2.5 in.**
Average Transfer Length (L_t) @ release	**-**
@ time of testing	**-**
Average NASP P.O value for strand "A"	**18.29 kips**

TEST SUMMARY

Load was applied in approximately 5.0 kips increments till the total deflection of 0.4 in. Further increments of deflection were set to 0.05 in up to 1.15 in. total deflection. Finally beyond this point up to failure the deflection was incremented by 0.1 in. DEMEC readings were taken at all load increments at both faces (East and West) with the rectangular rosette pattern at 36 in from the end being tested.

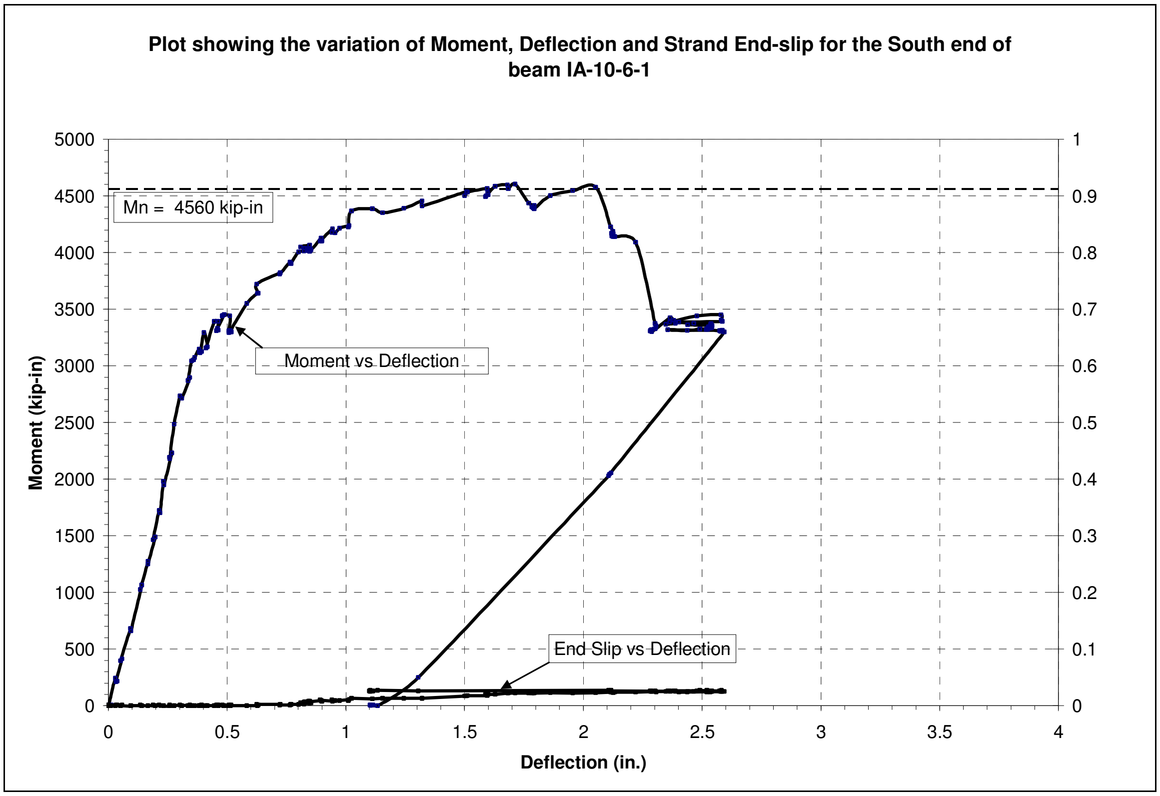
First flexural crack was observed at the load of 65.7 kips (Shear = 43.8 kips; deflection = 0.33 in.) A single crack was noticed at Stn. 66 at this stage. No significant drop in load was recorded. First secondary crack was noticed at Stn. 78 at the load of 77.6 kips (Shear = 51.7 kips; deflection = 0.45 in.)

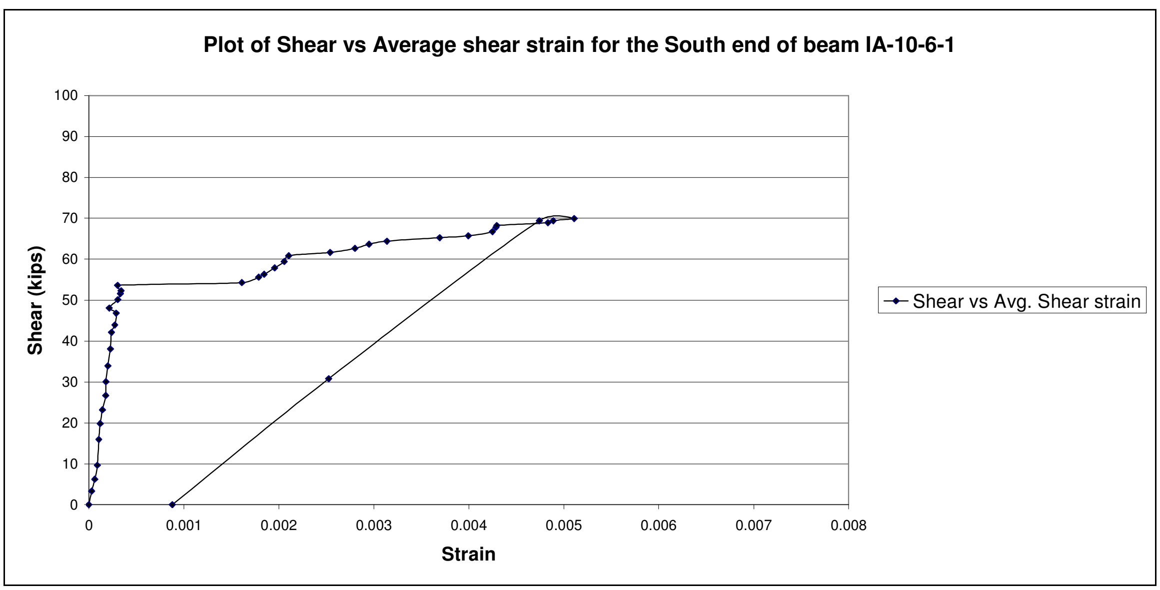
At the load of 80.6 kips (Shear = 53.7 kips ; deflection = 0.5 in.) an inclined flexure-shear crack was noticed near the first loading point from the South end. First web shear cracks were observed at the load of 81.6 kips (Shear = 54.4 kips; deflection = 0.58 in.) The value of load dropped to 77.2 kips after these cracks were formed. These web shear cracks formed one after another starting from the first loading point nearest to South support and moving towards South support.

First end slip of 0.01 in. was observed at the load of 92.7 kips (Shear = 61.8 kips; deflection = 0.9in.) End slip value went on increasing very slowly with every load increment until at strand fracture, the maximum value of end slip was 0.03in.

As more flexural cracks continued to occur after the first one, it was noticed that the spacing of flexural cracks towards the South side of loading points was smaller than that on the North side of loading points.

A sudden violent noise was heard at the load of 105 kips (Shear = 70 kips; deflection = 2.5 in.). Load value dropped to 94 kips.After careful observation of the widest crack where concrete spalling took place, it was noticed that one of the strands (Bottom East) had fractured.





(In all the photographs presented below, cracks marked in black represent the ones originated as flexural cracks while those marked in blue represent the web shear cracks. Red color was used only for marking the grid lines and station points. Number written in red should not be confused with the load values.)

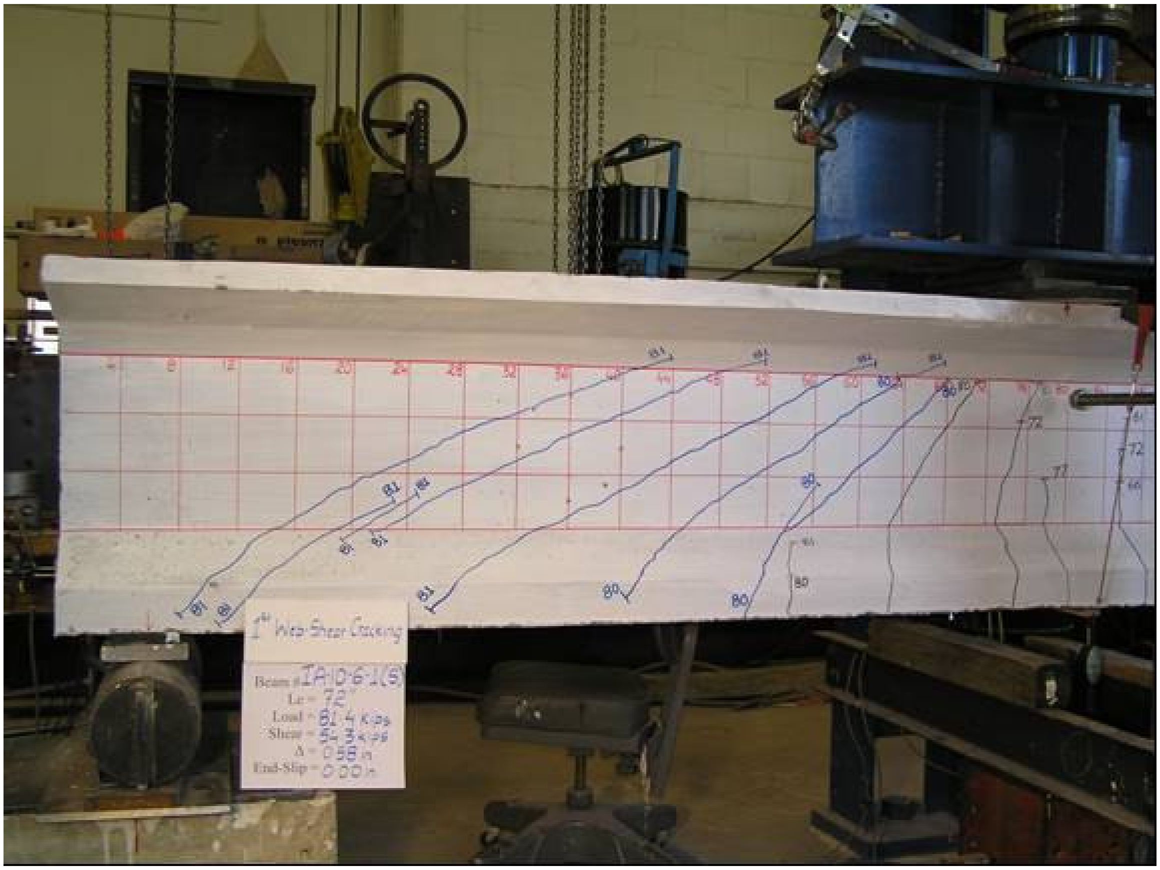


Photo of the South end of the beam IA-10-6-1 showing the first web shear cracking

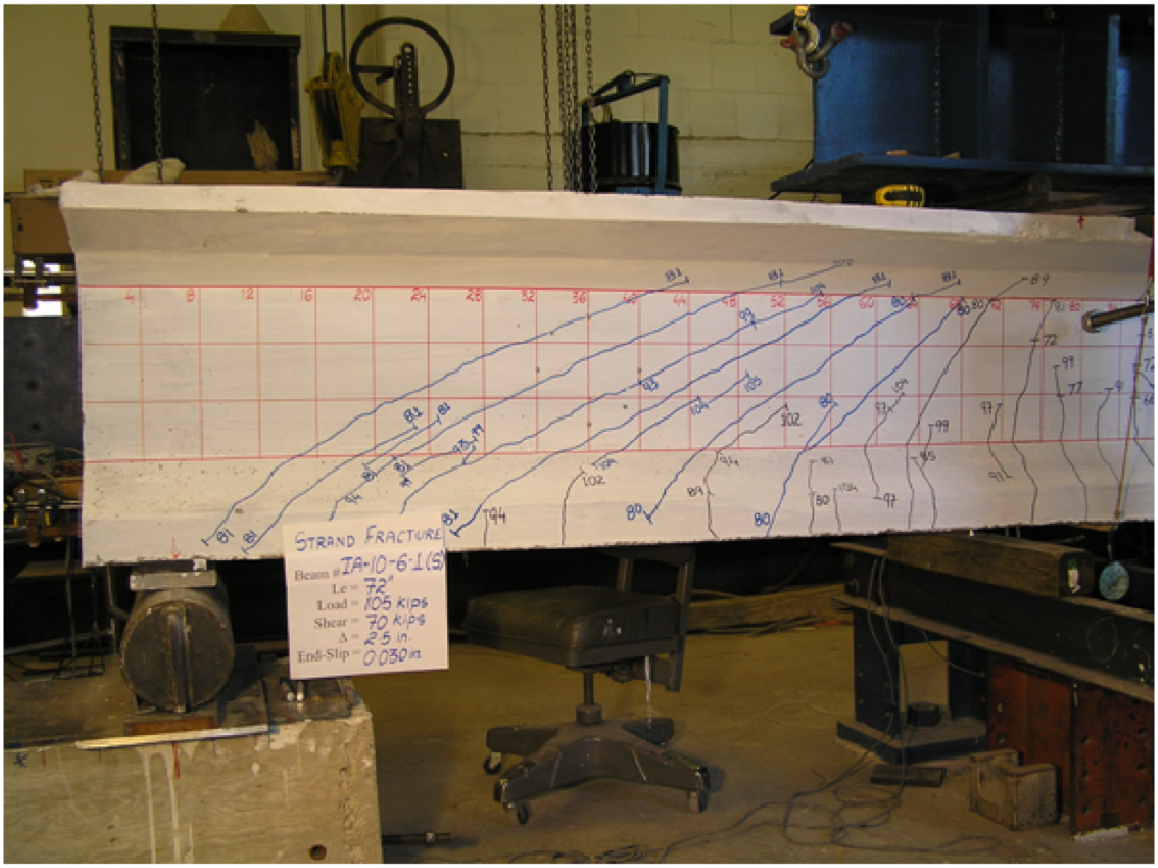


Photo of South end of beam IA-10-6-1 showing the cracking pattern at strand fracture

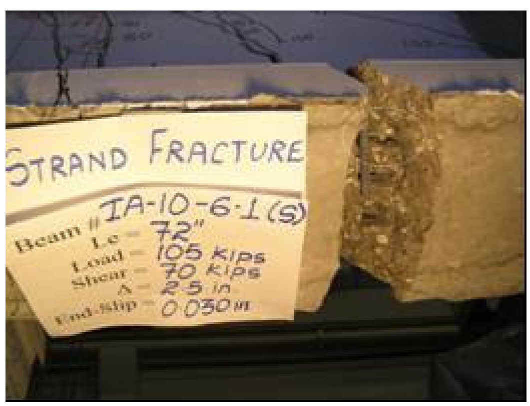


Photo showing the fractured strand (Test : IA-10-6-1-S)

BEAM NAME: IA-10-6-2
END: NORTH
DATE: 10/2/2005

TEST PARAMETERS	
Concrete Compressive Strength	**14930 psi**
Embedment Length(L_e)	**72 in.**
Span	**222 in.**
Failure Mode	**Shear failure at opposite side**
Maximum Load	**67.8 kips**
Maximum Shear	**45.2 kips**
Maximum Moment	**2983.2 kip-in**
Maximum Deflection attained	**0.9 in.**
Rebound after complete unloading	**0.4 in.**
Average NASP P.O value for strand "A"	**18.29 kips**

	Transfer lengths (in.) for beam # IA-10-6-2		
		At Release	At the time of testing
North	Top	21.43	23.43
	Middle	16	-
	Bottom East	16.12	22.51
	Bottom Central	10.93	50.43
	Bottom West	17.82	20.53

TEST SUMMARY

Before starting the test, strands at the South end were prevented from slipping with an arrangement of chucks as shown in the photo below.

Load was applied in approximately 3.0 kips increments till first flexural cracking. Beyond this point the deflection was incremented by 0.025 in. till the end of the test. DEMEC readings were taken at all load increments at both faces (East and West) with the rectangular rosette pattern at 36 in from the end being tested.

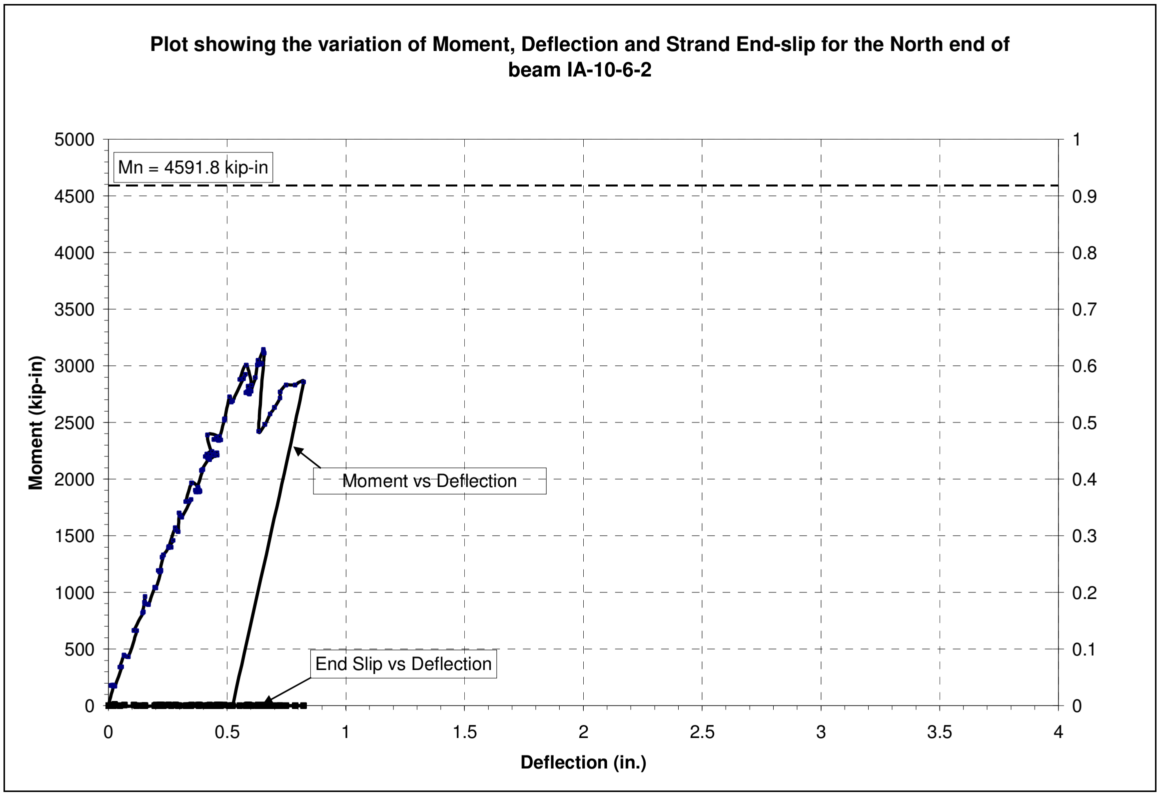
Even before the first flexural cracks were formed, an inclined crack originating from the initially existing cracks on the other side was noticed. The load at this point was 18 kips (Shear = 12 kips ; deflection = 0.18 in.). More and more audible cracks continued to form near the South end support along with spalling of concrete.

At 55.7 kips (Shear = 37.1 kips; deflection = 0.63 in.) a prolonged cracking sound was heard near the south support with load value dropping to 50.7 kips.

First flexural crack was observed at the load of 64.9 kips (Shear = 43.3 kips; deflection = 0.8 in.) A single crack was noticed at Stn. 86 at this stage. No significant drop in load was recorded.

For this particular test, there was no web shear crack noticed in the North side shear zone. The loading was stopped when the beam was observed to have failed in shear near the South support. The maximum load reached was 67.8 kips (Shear = 45.2 kips; deflection = 0.9 in.)

End-slip value remained 0.00 throughout the loading cycle.


Plot showing the variation of Moment, Deflection and Strand End-slip for the North end of beam IA-10-6-2
Mn = 4591.8 kip-in
Moment vs Deflection
End Slip vs Deflection
Moment (kip-in)
Deflection (in.)
0
500
1000
1500
2000
2500
3000
3500
4000
4500
5000
0.5
1
1.5
2
2.5
3
3.5
4
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9

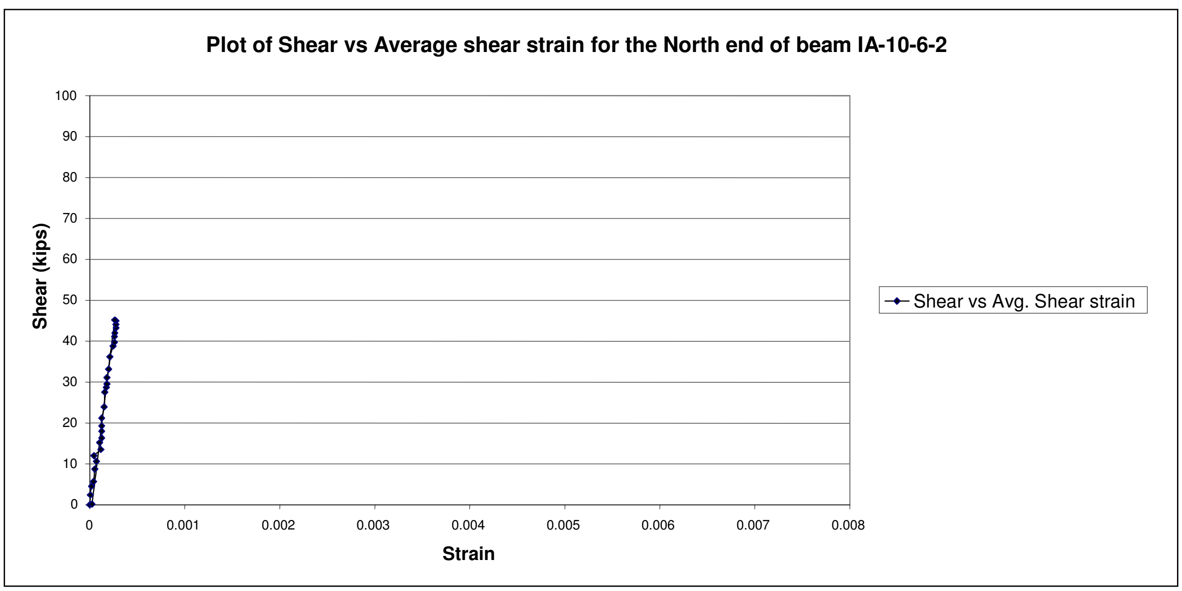

Plot of Shear vs Average shear strain for the North end of beam IA-10-6-2
Shear (kips)
Strain
Shear vs Avg. Shear strain
0
10
20
30
40
50
60
70
80
90
100
0.001
0.002
0.003
0.004
0.005
0.006
0.007
0.008

Photo of the North end of the beam IA-10-6-2 showing shear failure in the South side shear zone.

BEAM NAME: IA-10-6-2
END: SOUTH
DATE: 10/20/2005

TEST PARAMETERS	
Concrete Compressive Strength	**14930 psi**
Embedment Length(L_e)	**88 in.**
Span	**270 in.**
Failure Mode	**Failure did not occur**
Maximum Load	**83.4 kips**
Maximum Shear	**55.6 kips**
Maximum Moment	**4559.2 kip-in**
Maximum Deflection attained	**5.7 in.**
Rebound after complete unloading	**3.4 in.**
Average NASP P.O value for strand "A"	**18.29 kips**

	Transfer lengths (in.) for beam # IA-10-6-2		
		At Release	At the time of testing
South	Top	6.16	19.36
	Middle	6.48	-
	Bottom East	6.42	10.64
	Bottom Central	9.45	NA
	Bottom West	2.90	NA

TEST SUMMARY

Load was applied in approximately 4.0 kips increments till first flexural cracking. Beyond this point the deflection was incremented by 0.025 in. till total deflection reached 1.0 in. Further increments of deflection were kept 0.05 in. After the total deflection reached 1.8 in. the deflection increment was set to 0.1 in. DEMEC readings were taken at all load increments at both faces (East and West) with the rectangular rosette pattern at 36 in from the end being tested.

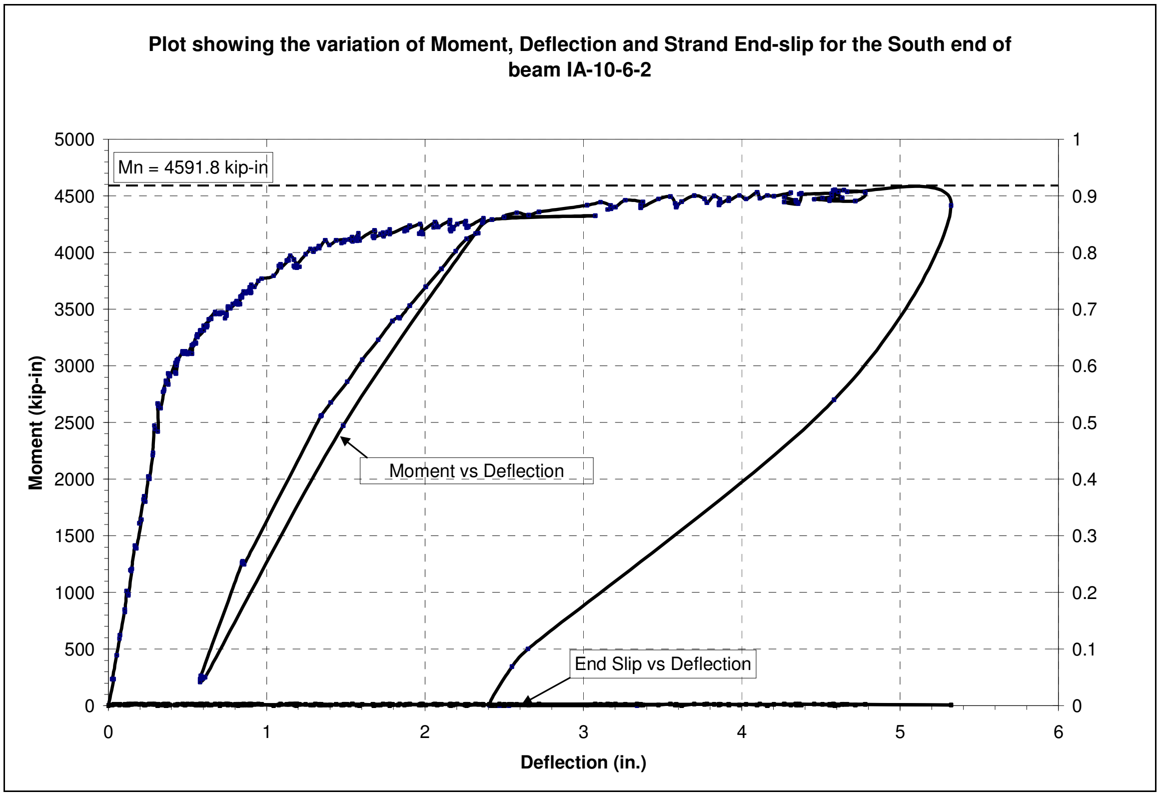
First flexural crack was observed at the load of 51.4 kips (Shear = 34.3 kips; deflection = 0.35 in.) A single crack was noticed at Stn. 96 at this stage. No significant drop in load was recorded.

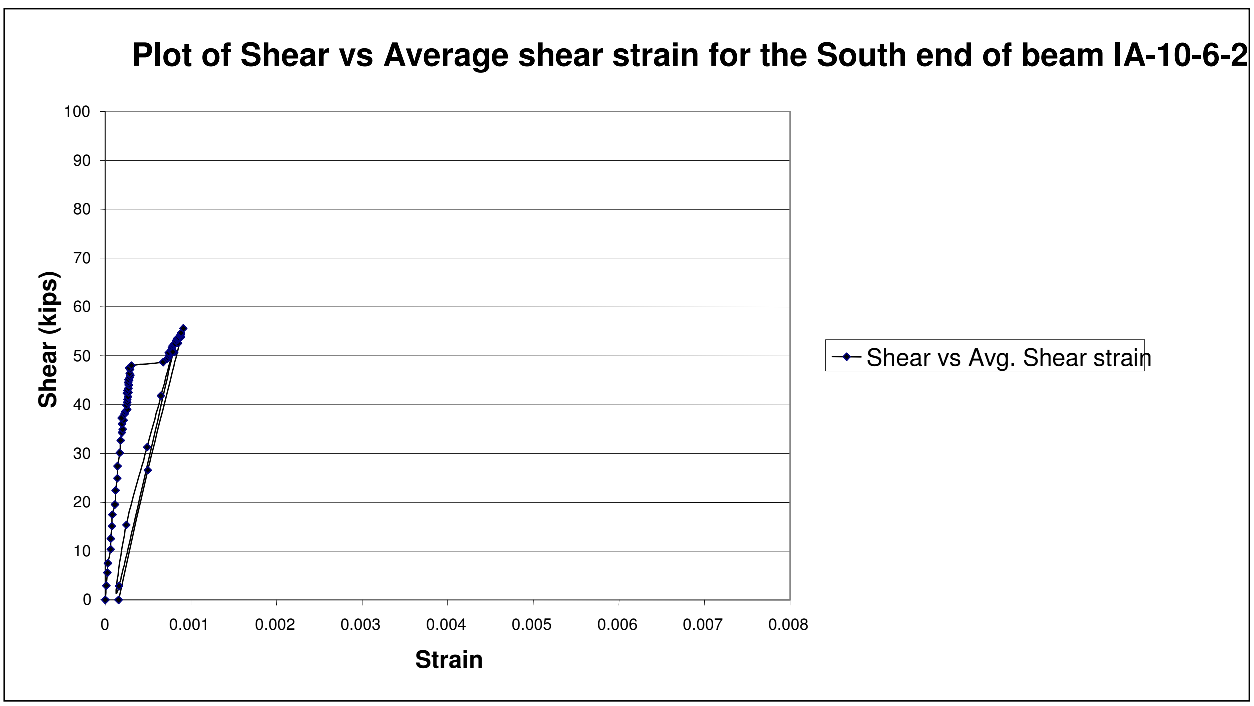
The load of 63.5 kips (Shear = 42.3 kips; deflection= 0.68 in.) an inclined flexural shear crack was observed between Stn. 68 and Stn 80. This crack was still not a web shear crack. The load value dropped to 63.4 kips after this crack occurred.

First web shear cracking was noticed at the load of 73 kips (Shear = 48.7 kips; deflection = 1.2 in.). These cracks occurred in the form a number of cracks almost parallel to each other in the shear zone.

No significant changes were noticed as the deflection was incremented further. Maximum deflection attained was 5.7 in. and load at this point was 83.4 kips (Shear = 55.6 kips). Crack width of the central crack was noted as 0.5 in. End slip value still remained 0.00in at both ends.

Further increments in deflection were not possible as the hydraulic ram had reached its limit. The beam was completely unloaded and the deflection, end slip and DEMEC readings were carefully noted.





(In all the photographs presented below, cracks marked in black represent the ones originated as flexural cracks while those marked in blue represent the web shear cracks. Red color was used only for marking the grid lines and station points. Number written in red should not be confused with the load values.)

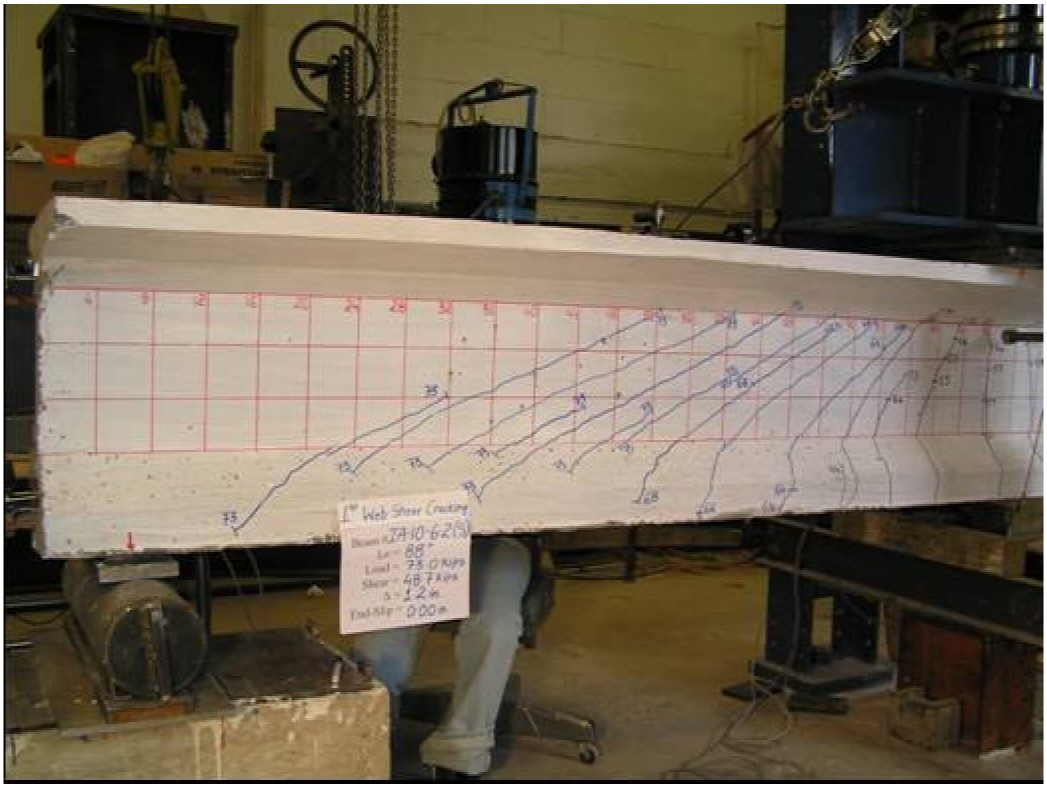


Photo of the South end of the beam IA-10-6-1 showing the first web shear cracking

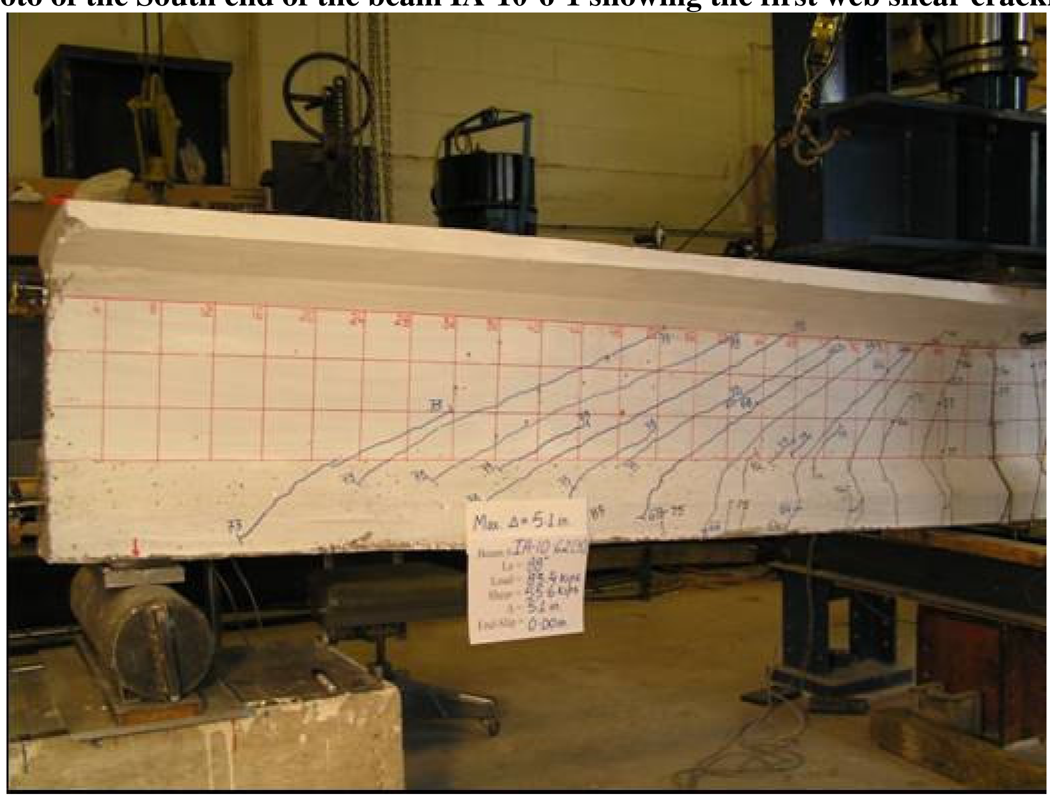


Photo of South end of beam IA-10-6-1 showing the cracking pattern at the maximum load (Deflection value in the photo is mistakenly written as 5.1 in. instead of 5.7 in.)

VITA

Amol Shridatta Ganpatye

Candidate for the Degree of

Master of Science

Thesis: RECOMMENDATIONS FOR THE DEVELOPMENT LENGTH OF PRESTRESSING STRANDS INCLUDING THE EFFECTS OF HIGH STRENGTH CONCRETE

Major Field: Civil Engineering

Biographical:

Personal Data: Born in Mumbai, Maharashtra, India on 21st January 1983, the son of Shridatta Prabhakar Ganpatye and Vidya Shridatta Ganpatye

Education: Graduated from Vinayak Ganesh Vaze College of Arts Science and Commerce, Mulund, Mumbai, February 2000; Received Bachelor of Engineering from University of Mumbai in May 2004. Completed the requirements for the Master of Science degree with a major in Civil Engineering and Structural Engineering as specialty at Oklahoma State University in December 2006.

Experience: Employed by the Oklahoma State University as a Graduate Research Assistant during August 2004 – May 2006 and as a Graduate Teaching Assistant for the course ENSC 2143 (Strength of Materials) for Fall 2004 and Fall 2006 semesters.

Professional Memberships:

1. The Honor Society of Phi-Kappa-Phi (November 2005)
2. Madison Who's Who of Professionals (2005)
3. International Who's Who Historical Society (2005)
4. American Society of Civil Engineers

Name: Amol Shridatta Ganpatye Date of Degree: December 2006

Institution: Oklahoma State University Location: Stillwater, Oklahoma

Title of Study: RECOMMENDATIONS FOR THE DEVELOPMENT LENGTH OF PRESTRESSSING STRANDS INCLUDING THE EFFECTS OF HIGH STRENGTH CONCRETE

Pages in Study: 287 Candidate for the Degree of Master of Science

Major Field: Civil Engineering

Scope and Method of Study:

Development length is a design requirement specified by the design codes for ensuring adequate anchorage of the prestressing strands. Current code provisions do not consider the effects of changing concrete strengths on the required development length. This research is focused on finding these effects and proposes a design equation, based on the experimental results, for calculating development length of prestressing strands. For this purpose, development length tests are carried out on multiple rectangular and I-shaped beams with various concrete strengths at Oklahoma State University.

Findings and Conclusions:

Experimental results clearly indicate that the bond between prestressing strands and concrete is improved as the concrete strength is increased. Appropriate changes to the current design code equations for development length are recommended. A minimum NASP Pull-Out value is suggested for safe use of the prestressing strands with respect to their anchorage requirements.

ADVISER'S APPROVAL: Dr. Bruce W. Russell