PERFORMANCE OF PAPER TUBES

by

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ABSTRACT

The tube performance requirements critical to a manufacturer's needs are dependent on such parameters as the manufacturer's processes, winding media, packaging, and equipment. Two important strength requirements for paper tubes include flat crush strength and radial crush strength. Flat crush strength is an industry standard test method and thus an understanding of this strength parameter is important for any user of paper tubes. This paper will present a description of flat crush strength as well as basic parameters related to flat crush. We will also present a patented approach to optimize flat crush strength. This patented approach is based upon experiments and finite element analysis. Another important paper tube performance property is radial crush strength. Radial crush strength is a critical strength parameter for manufacturers of films and textiles or other media that have high recovery rates in the machine direction. This paper will present a Sonoco patented tester for radial crush strength as well as basic parameters related to radial crush. Finally, this paper will present some basic information on tube behavior with changes in tube moisture content.

INTRODUCTION

Spirally wound paper tubes are fabricated by immersing paperboard plies in an adhesive bath and then winding plies around a mandrel in a staggered fashion. Plies are driven by a rubber belt so that the fabricated tube moves circularly around the mandrel until a saw cuts it to the desired length. The manufacturing process is illustrated in Figure 1.

Spiral paper tubes are commonly used in industry as a structure for winding paper, film, or textile yarns during production operations. Paper tubes are also used at construction sites as forms for concrete columns. In these applications, paper tubes are subjected to a wide variety of loading conditions, often complicated by different support or chucking mechanisms.

Paper is a unique orthotropic material. The ratio of moduli in the one (machine) and three (Z) material directions can be more than 100 (1, 2). Moreover, spiral tubes are quite anisotropic as tube geometric axes do not coincide with the principal directions of the paper. These tubes can also be quite thick: thickness to diameter ratios of 1/5 are not unusual. As discussed by Gerhardt (3) for certain loadings, these complexities cause deformations in paper tubes that can differ significantly from that predicted by standard theories.

Two important strength parameters of paper tubes are flat crush and radial crush. These parameters are discussed in more detail below. In addition, some basic information pertaining to tube behavior with changes in moisture content are also discussed in this paper.

FLAT CRUSH STRENGTH

In a flat crush test, a 101.6 mm (4 inch) length of tube is placed sideways between two steel platens. Flat crush strength is the maximum force developed as the platens compress the tube. A schematic is shown in Figure 2. Loading rate and other details are described in CCTI T-108 (4).

Flat Crush: Multi-Grade Tubes

Strength properties of different grades of recycled paper can vary as much a 3:1 ratio. Stronger, denser paperboard is made from higher quality recycled furnish and run at slower production rates. Therefore, developing a methodology to fabricate paper tubes using an optimized, multi-grade structure can offer significant cost savings. Details of this construction are contained in Patent 5,393,582 (5).

We designed experiments to measure strength of various multi-grade constructions. Specifically, tubes were fabricated with two grades of recycled paper with different strength levels. A variety of tubes were fabricated with plies of A and B located in different positions through the tube wall thickness. For example, Figure 3 is a schematic of a tube fabricated from 50% A and 50% B. In this example, grade A is located about halfway through the thickness of the tube.

We fabricated 10 different tube designs by positioning strong and weak grades in different locations in the tube wall. All tubes were fabricated using 9 plies of A and 9 plies of B. All tubes were 76.2 mm (3 inch) inside diameter and about 10.8 mm (0.425 inch) thick. Strength results are shown in Figure 4, where each data point represents average strength for one particular type of tube. The symbols illustrate positioning of grades A and B in the tube wall. The dark section shows the location of the stronger paper, grade A. Note that tubes on the left and right extremes have grade A on the inside half, and outside half of the tube wall, respectively. Tubes on the upper line represent configurations where stronger paper is located in the center of the tube wall. Data from tubes fabricated from other percentages of A and B is presented in Patent 5,393,582 (5).

To interpret these experimental findings, we conducted extensive finite element simulations. Tubes with inside diameters ranging from 50.8 - 508 mm (2 - 20 inch), thickness from 1.27 - 25.4 mm (0.050 - 1.000 inch), and spiral winding angles of 15 - 85 degrees were analyzed. Using this extensive numerical data, regression was used to capture peak stress values as functions of these geometric variables. Moreover, a design methodology was developed from these regression equations and experimental results.

The design equations themselves are proprietary and cannot be reported here. However, comparison of predicted and experimental results is shown in Figures 5 and 6.

Figure 5 compares predicted strength with data from discussed previously. Note that agreement is not perfect, but the design methodology captures the impact of moving higher strength paperboard into different locations in a tube wall.

Figure 6 shows independent flat crush predictions for 62 different multi-grade tube designs. Tubes were fabricated from both two and three different grades of recycled paperboard. The figure shows predicted strength on the Y axis and experimental strength on the X axis. If agreement was perfect, every tube would fall on the line shown. Agreement is excellent and average error is only 5.3%.

The derived flat crush design equation automatically incorporates finite element results for this loading. Thus, the impact of changing tube wall thickness or winding angle are accurately built into the model. As shown in the next section, we can also adjust strength to account for tube moisture content.

In additional research, we evaluated this equation using experiments on over 500 different tubes. Over this large database, average error is only 5.8%. With this technology, we believe we can reliably engineer tubes to meet our customer's flat crush specifications.

Moisture Content

Changes in paper tube strength and stiffness with changes in moisture content are significant. As tubes are used in a variety of environmental conditions, quantifying how each performance attribute changes with moisture content is important.

Data in Figure 7 illustrates flat crush dependency on moisture content. In all, 8 different tube types were tested. Data was normalized by adjusting flat crush strength to 1.0 at a moisture content of 8.0%. In the field, a typical moisture content range is 12% to 6%. Data suggests that as tube moisture decreases from 12% to 8%, flat crush increases. As tube moisture content is reduced below about 7%, flat crush decreases. This is consistent with graph 2 in CCTI -TCR-2 (6).

TUBE RADIAL CRUSH STRENGTH

Flat crush strength provides a general measure of tube strength. However, this loading does not simulate some field applications. As mentioned previously, a web material is typically wound around paper tubes in a manufacturing operation. Depending on the wound medium, this operation can result in significant pressure on tube outside diameter. We developed a test device to test tubes under this type of loading condition. Measured tube strength is called radial crush. Figure 8 below illustrates the difference in loading conditions between flat and radial crush conditions.

Radial Crush Tester

Figure 9 is a schematic of a tester developed to measure tube radial crush strength. A closed hydraulic system produces pressure on an annular rubber bladder. Ball bearings are placed between tube outside diameter and this bladder. As pressure is increased, pressure is transmitted through the ball bearings to the core. The ball bearings inhibit core buckling. In fact, tube failure patterns from radial crush testing are very similar to those found in field failures caused by excess winding pressure. Full details of this device are described in Patent 5,339,693 (7). Data that verifies the functionality of this test is also presented by Saliklis and Rowlands (8).

Radial crush strength of paper tubes was measured with inside diameters ranging from 76.2 - 254 mm (3 - 10 inch). These tubes were fabricated from a wide range of paper strength levels. By analyzing tube and paper strength, we developed a proprietary design methodology for radial crush strength. This methodology estimates strength based on tube ID, wall thickness, spiral winding angle, paper strength and moisture content.

A comparison of experiment and theory is shown in Figure 10. Each data point is the average of 10 radial crush tests from a particular tube type. Note that the design methodology estimates radial crush strength with an average error of only 5.5%.

We evaluated the relationship between flat and radial crush using the same data set. As shown in Figure 11, there is a general correlation. However, note that tubes with radial crush of roughly 400 psi have flat crush strength ranging from 200 to 500 (lb/4in). Therefore, radial crush test is more reliable for measuring strength required in field applications involving high pressure winding operations.

Using this technology, spiral paper tubes are designed to desired levels of radial crush strength. During customer trials, we can estimate pressures at film/core interfaces using tubes with strain gage and/or pressure sensor instrumentation. This enables designing tubes for specific applications. However, the issue of creep/moisture content must be addressed in the design process as: (1) loading rate in the radial crush test is higher than field loading and (2) for some films, microstructure changes over time cause pressure changes.

Moisture Content

Radial crush strength is highly sensitive to tube moisture content. Data from a variety of tube types is shown in Figure 12. Radial strength of tubes in this experiment varied by a factor of 3:1 and strength was normalized to give 100% at a 6% moisture content. In field applications, typical moisture ranges vary from 6% to 12%.

Tube Dimensional Stability

The dimensional stability of paper tubes (ie. inside diameter, outside diameter, wall thickness, and length) are highly dependent on changes in tube moisture content. Paper is a hygroscopic material and thus will change dimensions as it absorbs or loses moisture. In addition to being hygroscopic, paper is also an anistropic material and thus the dimensional changes in the length, width, and thickness of the paper are not uniform. This is further complicated by the fact that the paper is generally slit into relatively narrow ribbons as shown in Figure 1 and wound at various spiral angles depending on the tube inside diameter and ribbon widths. Thus, the magnitudes of changes in tube dimensions with changes in moisture content will vary with different spiral angles and geometries. However, some general rules of thumb for changes in tube dimensions with changes in moisture content are presented in Table 1.

The information in this table is contained in the CCTI report TCR-2 (6). One should keep in mind that this information is intended to serve as a guideline only. Actual dimensional changes will vary depending on the tube and paper geometries. This report also contains some general information about the dependence of other paper tube strength properties on tube moisture content.

SUMMARY

Flat crush is an important tube strength parameter and is the most commonly used parameter throughout the industry to specify paper tube strength. It is an easy test to perform and thus has been adopted throughout the industry. However, flat crush is not the critical strength parameter for many winding operations. In many winding operations tube radial crush strength and other parameters such as inside diameter stiffness and outside diameter stiffness are much more representative of the actual loading conditions on the tube. The critical tube strength parameter(s) can vary significantly depending on such criteria as the winding equipment, wound media, packaging, processes, etc.

Almost all paper tube properties (strengths and dimensions) are significantly affected by tube moisture content. This very important characteristic of paper tubes cannot be ignored in any application and must be taken into consideration in order to ensure a proper tube design. Tube moisture content is dependent on the environment to which the tube is exposed. Some general guidelines for tube moisture content versus relative humidity are contained in table 3 in CCTI – TCR – 2 (6).

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8. Saliklis, E.P., Rowlands, R.E., "A Novel Radial Compression Testing Device for Tubes.", *TAPPI Journal*, Vol. 80, No. 1, p. 231-237, 1997.

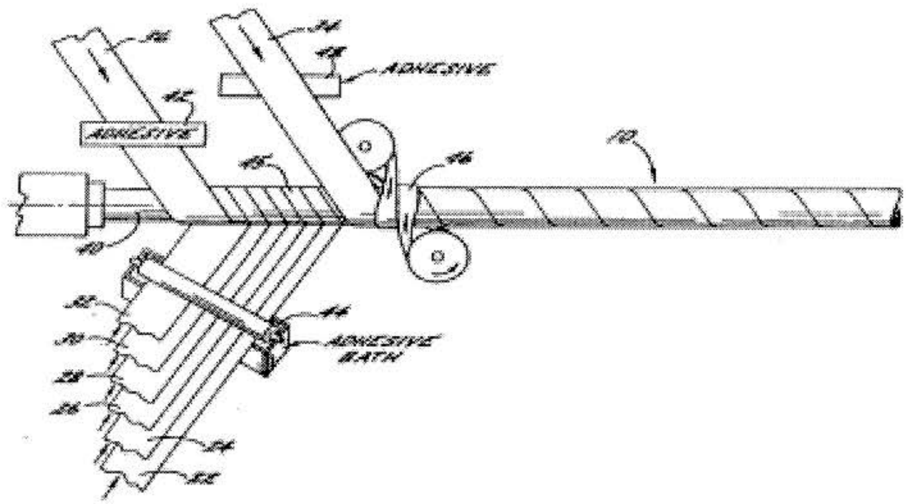

Figure 1
Schematic of Paper Tube Manufacturing Process

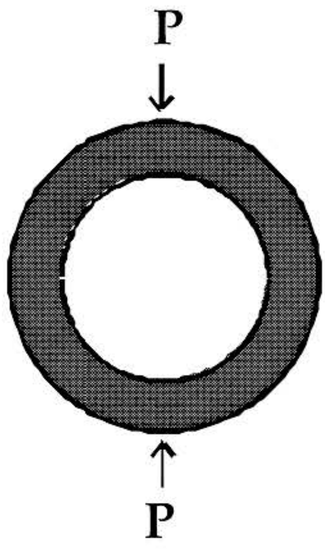

Figure 2
Flat Crush Loading

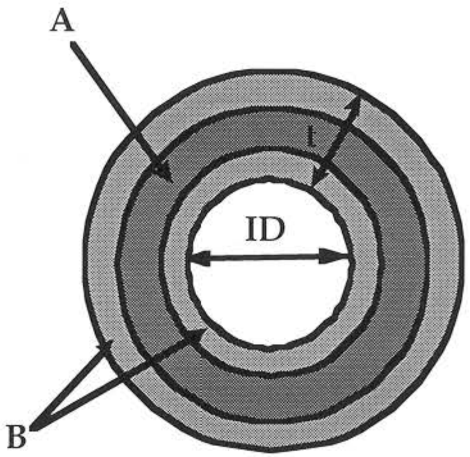

Figure 3
Multi-Grade Paper Tube

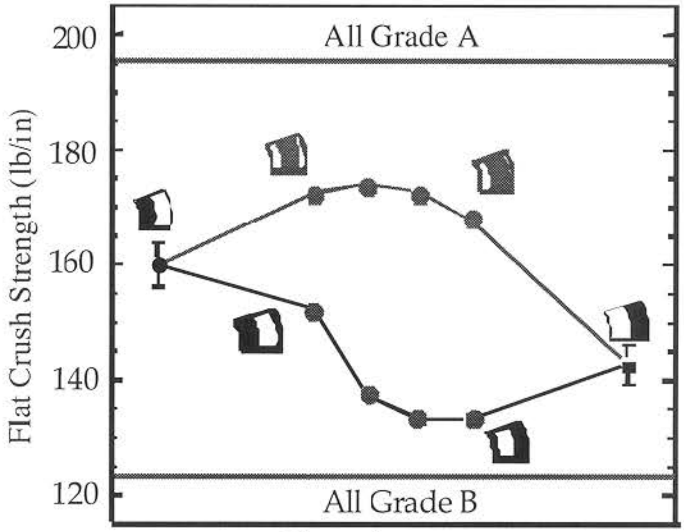

Figure 4
Multi-Grade Flat Crush Data
1 (lb/in) = 1.75 (N/cm)

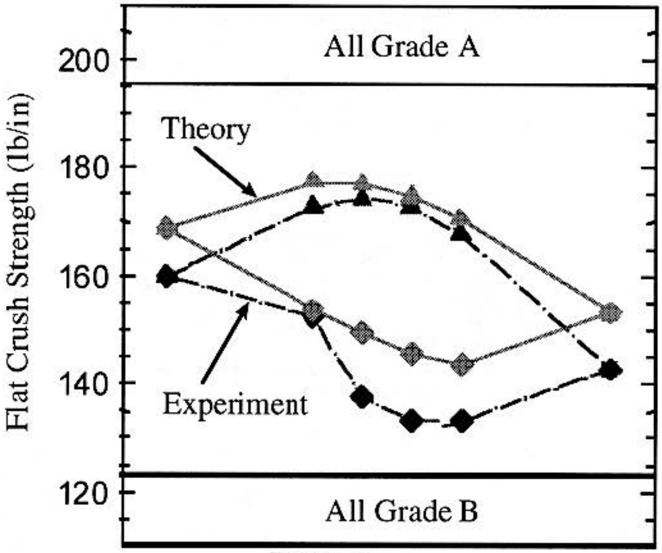

Figure 5
Multi-Grade Flat Crush Data:
Experiment vs. Theory
1 (lb/in) = 1.75 (N/cm)

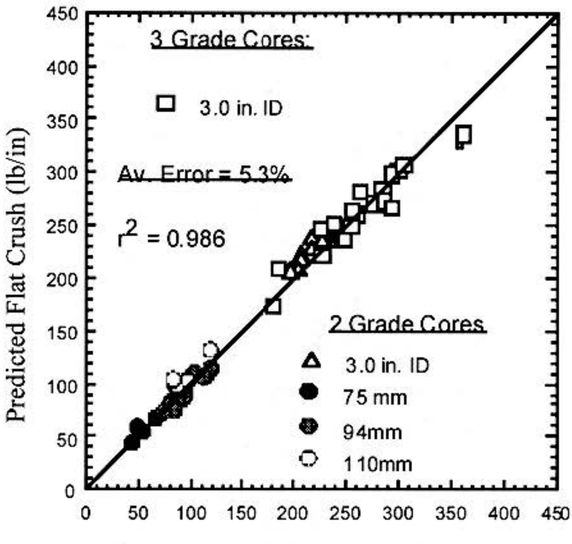

Figure 6
Independent Flat Crush Predictions:
62 Multi-Grade Tubes
1 (lb/in) = 1.75 (N/cm)

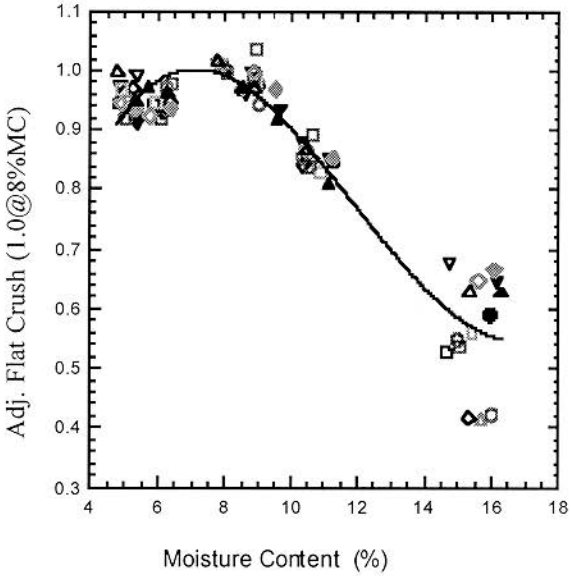

Figure 7
Flat Crush vs. Moisture Content

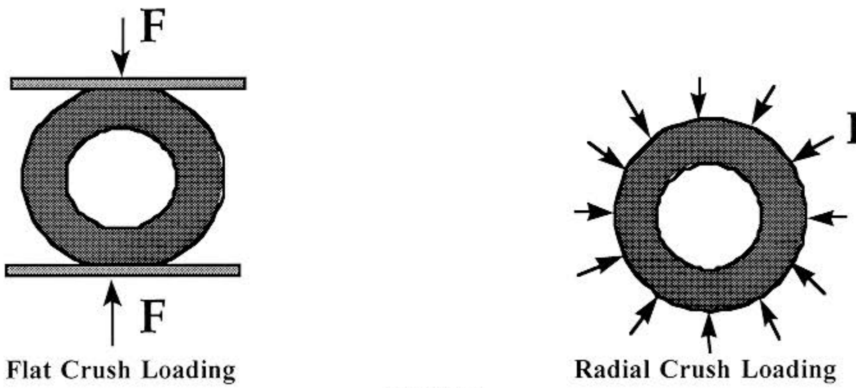

Figure 8

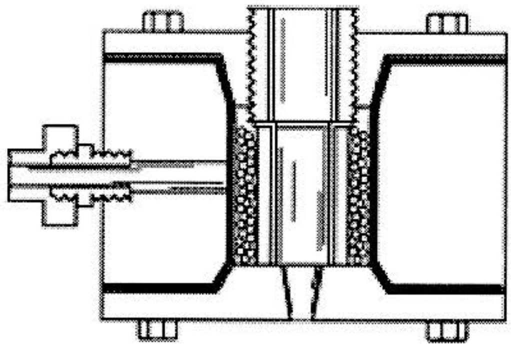

Figure 9
Radial Crush Tester

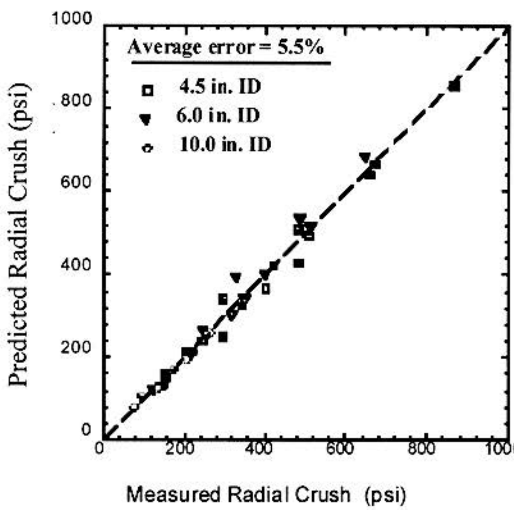

Figure 10
Radial Strength Data:
Experiment vs. Theory
1 (psi) = 689.5 (N/m^2)

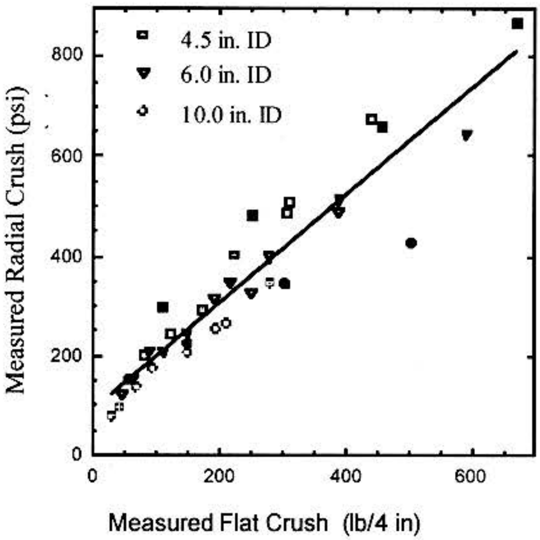

Figure 11
Flat vs. Radial Crush Data
1 (psi) = 689.5 (N/m^2);
1 (lb/4in) = 0.438 (N/cm)

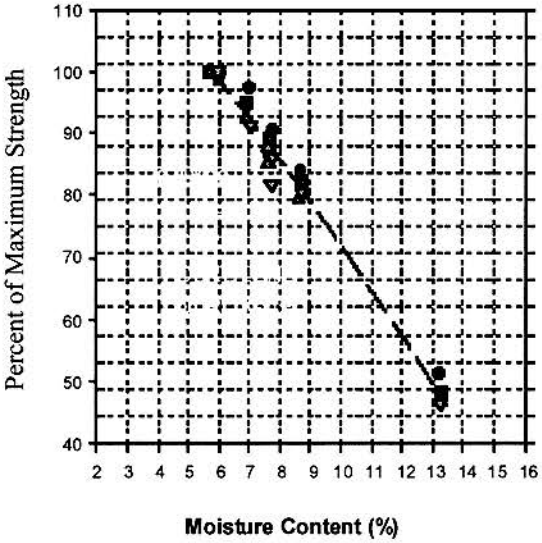

Figure 12
Radial Crush vs. Tube Moisture Content

Tube Parameter	Dimensional change factor per percent change in moisture content
Length	0.12%
OD	0.09%
Wall Thickness	0.06%
ID	0.03%

Table 1: Dimensional change factors for various tube dimensions per percent change in moisture content.

D.E. Rhodes, E. Yarborough, C.G. Johnson, Y. Wang and T.D. Gerhardt
Performance of Paper Tubes
6/8/99 Session 2 11:15 - 11:40 a.m.

Question:
Are there standard sizes developed on tube properties or do you have any catalogues with these properties?

Answer – David Rhodes, Sonoco
We do not have a catalogue prepared. These properties are different for all tube constructions. It would be very difficult to put this information in catalogue form due to the number of variables involved. However, we can readily give you this in formation for specific cores.

Question:
How much interest do you have in plastic cores?

Answer – David Rhodes, Sonoco
We make plastic cores and sell them. We try to match the product with the customer's needs. There are pros and cons to both plastics and paper. We take these into consideration when making recommendations for a specific applications. We also make composite cores for certain applications.

Question – David Pfeiffer, JDP Innovations Inc.
in radial crush test what is the point at which failure does occur?

Answer – David Rhodes, Sonoco
Failure occurs when we see a drop in pressure of a certain percentage.

Comment - Gary Homan, Westvaco
Your presentation justified my coming here. I am here to come up with a rule of thumb on dimensional changes on cores so this has been a good couple of days. You stated that the relation between radial and flat crush was not statistically good, but you failed to give R squared or error coefficient.

Answer – David Rhodes, Sonoco
I don't have an R^2 value for this relationship with me. The R^2 value will be different for different geometries and tube constructions. The main reason we pursued the radial technology effort is that the correlation between flat and radial crush is not good thus justifying research efforts on radial strength parameters.