WEB HANDLING TECHNOLOGIES, PAST, PRESENT AND FUTURE

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ABSTRACT

This paper gives a brief description of the evolution of technical knowledge. The evolution of beam theory is given as an example from the field of strength of materials. Technical knowledge starts with information gained from early experiences. These experiences are enhanced with empirical data gained through experimentation. Theories are developed to help explain the observations and experimental results. First principle understanding (models) are developed and experimentally verified. Over time these principles prove valuable and gain acceptance.

Published web handling information is reviewed and evaluated on this evolutionary scale for the topics of; winding, longitudinal dynamics and tension control, wrinkling, lateral mechanics, traction, air support conveyance, measurement/sensors, air entrainment, slitting and nip mechanics. Direction is given for future research needs in these technology areas.

A BRIEF HISTORY OF IWEB

Figures 1-7 illustrate statistics about the first decade of IWEB conferences. The attendance at the previous five IWEB conferences has been in the range of 150-200 people. The number of papers presented has grown from 22 to 38. This growth in presentations has required the use of split sessions to maintain the three-day format. There has been an excellent balance between number of papers presented by industry and research organizations. Two thirds of all the papers have been presented by authors from the United States. Winding and tension control have been popular topics, combining to cover more then half of all papers. These two popular topics show interesting trends in the balance between the theoretical and experimental nature of papers presented at IWEB. Figures 5 and 6 show that tension control started in 1991 as all theoretical and has trended toward more of a balance between theory and experiment. Winding on the other hand started very experimental in nature and has trended toward theoretical.

A BRIEF HISTORY OF STRENGTH OF MATERIALS [1]

Many people who work in the web handling field are mechanical engineers or have had some introduction into the field of strength of materials. Strength of materials is a centuries old field of engineering with a well-documented history [1]. Web handling on the other hand is a relatively new technology. The field of web handling can benefit from knowledge about strength of materials, but also knowledge of the process of scientific advancement.

The ancient Egyptians built great pyramids and monuments almost 5000 years ago. The Romans and Greeks built roads, bridges and building, some of which are still in use today. The great cathedrals of Europe were built about 1000 years ago. All these great projects were completed without fundamental knowledge of strength of materials.

Construction on the Cathedral in Cologne Germany was started 200 years before Leonardo da Vinci experimented with the strength of beams in the late 1400's. He discovered that the strength of a simply supported beam varies inversely as the length and directly as the width. He mentions nothing about the beam depth. He also stated "Mechanics is the paradise of mathematical science because here we come to the fruits of mathematics". His work was never applied to architectural structures.

Around the year 1600, Galileo discovered da Vinci's work and thought this new field of science could be applied to ship building. He experimented with tensile testing and found that the strength of a bar is proportional to the area. He also experimented with the strength of beams. Galileo came up with theoretical formulas for the strength of beams. Galileo's formula did not correlate well with his experimental data, because of his lack of understanding of yield stress and the neutral axis. Irregardless of this discrepancy, his equations were used for the next 200 years

In the late 1600's Hooke looked at the deflection, as well as the strength of beams. He realized that beams have both tension and compression. He also discovered the linear relation between force and displacement.

Also in the late 1600's Mariotte investigated elastic deformations. He understood the neutral axis, but put it at the bottom of the beam instead of the middle. His formulas were better at predicting experimental data, but were still incorrect. He dismissed the discrepancy as an effect of time.

At about the same time, the Bernoulli family developed elastic curves. The use of calculus on these curves led to the discovery of the proportional relationship between the applied moment and the curvature of a beam.

In the 1700's Euler used calculus (maxima, minima and infinitesimal elements) to develop two methods of beam analysis, the direct and minimum potential energy, and proved they are equivalent. He also investigated the effect of beam depth. Through most of his work he used the beam height cubed instead of to the fourth power. Only in his later years through much experimentation did he finally adopt the correct relationship.

In 1826 Navier published a book discussing the concepts of elastic limit, permanent set, the position of the neutral axis at the centroid of the cross section, the concept of breaking up the constant of proportionality into a material property (elastic modulus) and geometry (moment of inertia). He also stated what we commonly call the beam equation.

$$EI\frac{d^2y}{dx^2} = M(x)$$

THE EVOLUTION OF TECHNICAL KNOWLEDGE

The history of strength of materials is a good example of the process of gaining technical knowledge. First, materials were used for structural components long before we had any fundamental knowledge of their strength. Similarly we steered, coated and wound webs long before we had any fundamental knowledge of web handling. Because of the lack of fundamental understanding cathedrals fell, ships sank, webs wrinkled and wound rolls telescoped. After loosing a few ships and numerous expensive stock rolls, we decided to study these problems.

The first step is usually experimental, what load can this beam take before it breaks? How much tram error can this web take before it wrinkles? What if we change the length, the width or the thickness? Why does it vary with the height cubed? Or is it the 4th power?

The next step is usually to empirically or statistically analyze the data. Galileo correctly stated "the strength of a simply supported beam varies inversely as the length and directly as the width" 200 years before concepts such as elastic limit, neutral axis and modulus of elasticity were fundamentally understood. These valuable pieces of the puzzle were known and used long before the big picture was fully understood.

Qualitative and quantitative theories are then developed to explain the experimental data. The early pioneers in beam theory found small discrepancies between their partial or erroneous theory and experimental data. Unfortunately great figures such as Galileo, Euler and Bernoulli dismissed these discrepancies, missing the opportunity to further advance their theory and greatly decrease the time required to reach a fundamental understanding. Today, scientific experimental techniques and statistics should be used to help determine the difference between experimental error and erroneous theory.

Over time theories are refined and the limitations and nuances are better understood. The theories that are used in practice, and prove to be valuable predictors of actual events, become fundamental knowledge.

1. Common Use -- Beams were widely used without fundamental understanding of their strength or deflection characteristics. Occasional failures lead to experiments into the strength of beams.
2. Experimentation -- Experimental data leads to empirical models for strength and deflection. Often these relationships are valid over the range of data that may be excessively small or large, or errors are made in the measurements or experimental methodology. Empirical models lead to speculation about the fundamental relationship.
3. Theory -- Fundamental relationships are theorized and stated mathematically. These mathematical relationships then need to predict phenomena over a wide range of inputs.
4. Verification -- When the theoretical relationships are successful at predicting experimental results and the limitations of the theory and valid range of inputs is understood the author considers the theory as verified. Potential users of the theory may still be skeptical.

5. Value and Acceptance --Over time the theory will be used to predict and explain related phenomena. If the theory proves valuable, it will grow in acceptance.

WINDING

Winding has been the single most popular topic at previous IWEB conferences, comprising over 30% of all the papers presented. Winding also has some of the oldest and most numerous reference lists.

Winding is well suited for both experimentation and theoretical modeling. Twenty-four winding models have been presented or referenced at previous IWEB conferences. The plethora of winding models prompted Doug Kedl, (1997 IWEB keynote) to state "Every web handler needs a good roll model". The model that is most commonly referenced came from Zig Hakiel [2]. This model predicts interlayer pressure and tension of a center wound roll, given the inputs of geometry, material properties and tension. Many subsequent papers have augmented this model to account for rider rolls, surface winding, interlayer slippage and torque capacity, air entrainment and viscoelasticity.

Many experiments have been run providing data in an effort to validate the models and model refinements. Pressure measurement techniques presented include FSRs (Force Sensitive Resistors), acoustic time of flight measurements, pull-tabs and WIT (Wound-In-Tension).

Several papers discussed interlayer slippage and nip induced slippage. Measurement techniques included the J-line, instantaneous J-line and camera based techniques. Numerous papers discussed radial modulus, modeling and measurement techniques. Air entrainment in wound rolls is an important topic and has been discussed in several papers.

Where does our knowledge of winding fall on the evolutionary scale of technical knowledge? We have developed experimental measurements and techniques, extensive experimental data and developed empirical relationships for many wound roll defects. We have a plethora of models and a good fundamental understanding of stress states in wound rolls. We have investigated only a few defects including web caliper and tension variations, corrugations, roll slippage, starring, core failure and dishing.

One might think that winding technology is well advanced on the evolutionary scale. Unfortunately our advanced knowledge of wound rolls stress states often lacks failure criteria and therefore has only been applied to a small fraction of common winding problems. David R. Roisum stated in his 1997 IWEB paper "Modeling and measurement have and will continue to provide insight and understand. However, these techniques have not been widely employed as they are more complex and not as discriminating as simple visual inspection". Duane Smith's book [6] "Roll and Web Defect Terminology" lists 42 winding related defects. Less than half of these defects have been addressed by IWEB conference papers. Many of these problems, such as roll damage, offset core and poor splice are logistical rather then winding process related. A wide gap still remains between our current technical ability and what will be needed to solve many winding problems.

LONGITUDINAL DYNAMICS AND TENSION CONTROL

Longitudinal dynamics and tension control has been the second most popular topic at IWEB conferences. The controls aspects of web handling is a small subset of the much larger field of automatic control systems.

IWEB papers have lively debated controversial topics such as dancers vs. loadcells, inertia compensated dancers and sensors vs. observers. We have heard about many modern control algorithms including state space, fuzzy, decentralized and self-tuning. Theory is very rich in the field of automatic controls, but when it comes to tension control in webs, the vast majority of systems are still basic PID loops. Three-term PID technology was introduced in 1922 by Minorsky for controlling ship steering. Why, with all the advances in modern control theory, are we still predominately using 80-year-old technology? Why are these modern control systems not being used on our factory floors? There may be numerous reasons for this discrepancy, but part of the reason may be illustrated in figure 7 with the imbalance between theory and experimental data. Without experimental benchmarking of actual systems theories can not be validated and will not be accepted over time and have the opportunity to be proven valuable. Other possible reasons could be that proven PID technology is good enough for most applications, associated technologies, such as computer processing speed, has not advanced enough to put these algorithms into use or that expense of implementation is not justified by the relatively small market for web handling drives.

WRINKLING

Wrinkling was the third most popular topic at IWEB conferences, but falls well behind the number for papers on winding or tension control. Wrinkling is a common and very expensive problem in the web handling industry. One of the earliest and most commonly referenced papers on wrinkling is "Prediction of Shear Wrinkles in Web Spans" [3] by L. S. Gehlbach, J. K. Good and D. M. Kedl. This groundbreaking paper presents experimental techniques and data, along with theoretical stress state models and a failure criterion. Numerous IWEB papers built on this knowledge of shear wrinkling with improvements in failure criteria, traction, and interaction between spans. A paper was also presented that predicted wrinkling due to out of plane twist. Several papers discussed the theoretical and experimental aspects of spreader rollers.

Knowledge of shear and twist wrinkles is well advanced on the evolutionary scale and has proven to be valuable to industry. Unfortunately there are wrinkles that often form in machine direction that can not be explained by shear and twist wrinkle theory.

LATERAL MECHANICS

Lateral mechanics and wrinkling have had similar popularity, as a topic at IWEB conferences. Passive and active guiding was commonly practiced long before the pioneering work of J. J. Shelton in "Lateral Dynamics of a Moving Web" [4]. This paper theoretically described, and experimentally verified, the statics and dynamics of steering guides.

IWEB papers on lateral mechanics have investigated guidance in unwinds, rewinds and air flotation ovens along with novel guiding techniques and web edge sensors. Numerous papers have discussed the lateral mechanics of non-uniform webs.

The knowledge of lateral mechanics, as applied to uniform webs, is well advanced on the evolutionary scale. The theory has been developed, experimentally verified and has proven valuable over time. Unfortunately this knowledge has not been compiled in the defining book on web guiding.

A few areas that are still fruitful for investigation and publication are the mechanics of non-uniform webs, interactions between web and controller dynamics (especially in air flotation systems), and the performance of commercial systems. Non-uniform webs do not have the same boundary conditions and response as the uniform web discussed in the Shelton paper. An experimental investigation of the performance of sidelay, steering and displacement guides or different vendor guides would be very interesting. The Shelton paper covered web dynamics and controller dynamics are well known, but the interaction of these systems, especially in air flotation ovens, would be very interesting.

TRACTION

The topic of traction has grown in popularity in the later years of the IWEB conferences. Our understanding of traction is critical to web handling topics such as slippage in wound rolls, lateral mechanics, wrinkling, scratching and tension control. J. D. McDonald, of the Pulp and Paper Research Institute of Canada, presented a keynote address "Understanding Friction" at the 1999 IWEB conference. His statement "(Traction) Problems can often be reduced to simple mechanical models, the models require the coefficient of friction of the material as an input. However, coefficient of friction of paper can be an elusive measurement which depends on measurement conditions and handling".

Traction papers presented at previous IWEB conferences have discussed interlayer slippage in wound rolls, wrinkling dependence on traction, moment transfer between web spans, air film effects, pull roller slippage, web scratching, and an inexpensive roll speed measurement method. Models have covered the spectrum from the simple belt equation, strip models, to more rigorous FEM models with elements allowing slippage. These models have given us insight into many web handling phenomena, but unfortunately still rely on the elusive coefficient of friction measurements.

Simple problems can often be understood with the basic belt equation and strip models. More complex situations will require further development of models, such as FEM, that can determine local stick and slip zones. Simple models and commercial code currently exists and are proving valuable, but our use and understanding of the constant "coefficient of friction" is still in the experimental stages.

AIR SUPPORTED CONVEYANCE

Three topics have been common among the air supported conveyance papers, web flutter, nozzle or jet theory and air turns (reversers). Commercial ovens are often designed for maximum heat and mass transfer. These ovens are capable of producing heat and mass transfer rates far in excess of our coating and web handling capability. The practical limit of the drying/curing process is often drying defects or web handling issues such as flutter, touchdowns or lateral instability.

Several papers have discussed web flutter with references from flag flutter, flow induced vibrations and aircraft stability. We have seen experimental results with stable/unstable operating regimes, vibration models and a few attempts at a failure criterion. What would prove valuable to the web handling industry is an ability to predict flutter conditions in current designs and optimize future designs. The current published knowledge of air supported conveyance falls well short of that goal.

Several papers discussed lateral stability in air supported conveyance systems. These papers presented simple static lateral mechanics models coupled with the effects of air support. The case of the dynamic interaction of air supported conveyance systems and the dynamics of guiding systems has not been experimentally or theoretically discussed.

The third topic, air turns or reversers, has had both experimental and theoretical investigations. Design criteria are starting to immerge, but more advancement in this area would be valuable to the web handling industry.

MEASUREMENT/SENSORS

Experimental data both starts and ends our quest for technical knowledge. The first step in an investigation is usually experimental. Measurement and sensors are crucial to obtaining this experimental data. One of the final steps is using experimental data to verify our theoretical models.

There have been a large number of measurement techniques and sensors presented at previous IWEB conferences including:

- Force sensing resistors, pull tabs, instrumented cores, acoustic time of flight measurements, nip induce tension effects, air entrainment and slippage measurements for wound rolls.
- Virtual tension sensors (observers), crossweb tension sensors, roller moment, shear and moment transfer techniques for web span measurements, along with a discussion on the limitations of roller reactions as a means to measure web tension.
- Measurement methods for wrinkling, wrinkle resistance and web spreading.
- Material property measurements such as modulus, radial modulus, coefficient of friction and surface characteristics.
- Miscellaneous measurements such as web edge position, roller speed, bearing drag, stress fields in slitting, paper core strength and web flutter.

AIR ENTRAINMENT

Air entrainment has been a popular topic at previous IWEB conferences. Two common areas of investigation are air entrainment in wound rolls and air entrainment between a web and a transport roller. These two situations are very similar and use the same theories. Previously developed foil bearing theory, commonly referred to as the Knox-Sweeney equation, has been shown to be a reasonable predictor of the air layer between a web and roller and between the outer wraps of a center wound roll. Previously developed elastohydrodynamic theory has been shown to be a reasonable predictor of the air layer between a web and nip rollers and between the outer wraps of a roll wound with a pack roller. The solution of these problems has proven difficult and computationally intensive, therefore numerical results have been fit to closed form parametric equations.

The knowledge of air entrainment in web handling is well advanced. Measurement techniques have been developed, experimental data taken and reasonable models verified.

SLITTING

There have been four papers on slitting presented at previous IWEB conferences. One paper was an overview of slitting and the others were technical papers on fracture mechanics. Fracture mechanics is a well-developed theoretical field, the application to web handling is relatively recent. Experimental techniques and measurements tend to be difficult.

NIP MECHANICS

Nip mechanics has been a very popular topic at previous IWEB conferences, but generally integrated into a broader topic such as winding, wrinkling and air entrainment. Nip systems are broadly used in web handling and winding processes. They also commonly cause problems, which prompted J. D. Pfeiffer [5] to investigate in his widely referenced paper "Mechanics of a Rolling Nip on Paper Webs".

The effect of a nip, or lay-on, roller on the wound in tension of wound rolls has been the subject of numerous IWEB papers. We have seen very interesting analysis and video of the movement between different laps of a winding roll. Several papers have discussed the air entrained under a nip roll, and how that relates to wound rolls and traction. The tension isolation ability of nip rollers has been studied for wound rolls and draw controlled web spans. The speed changes of the rubber surface through the nip zone has been studied and related to Poissson's ratio. These speed changes have been shown to cause guiding problems along with wrinkling problems such as "rivers" and "lakes".

The knowledge of nip mechanics has been widely studied. We have seen interesting experimental methods and data. Closed form and numerical models have been presented and compared to experimental data. Time will determine if these models grow in acceptance and prove valuable.

ACKNOWLEDGMENTS

I would like to thank the presenters and organizers of the first decade of IWEB conferences. The IWEB conferences has truly succeeded in its goal of providing a forum in which engineers and scientists of various countries could present the results of their research and exchange ideas.

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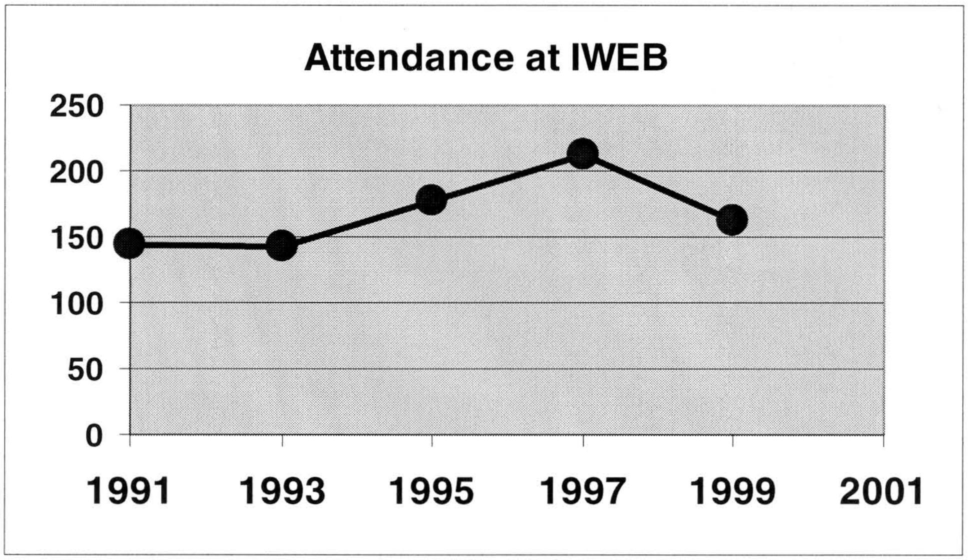
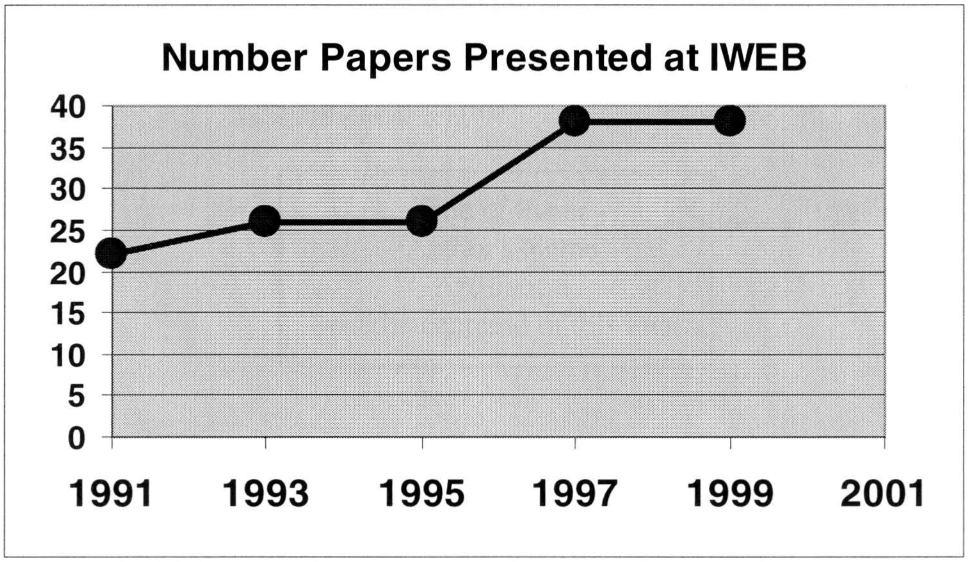


Figure (1)



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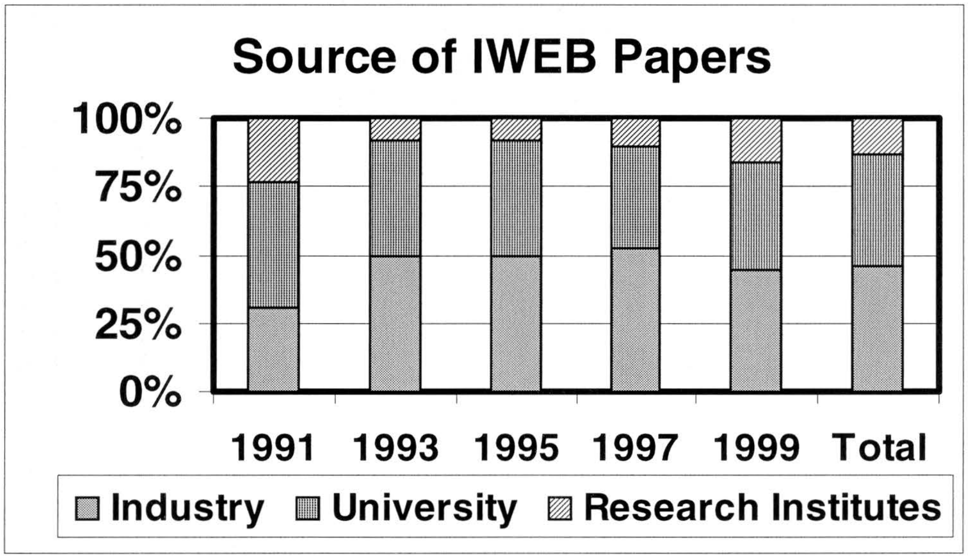

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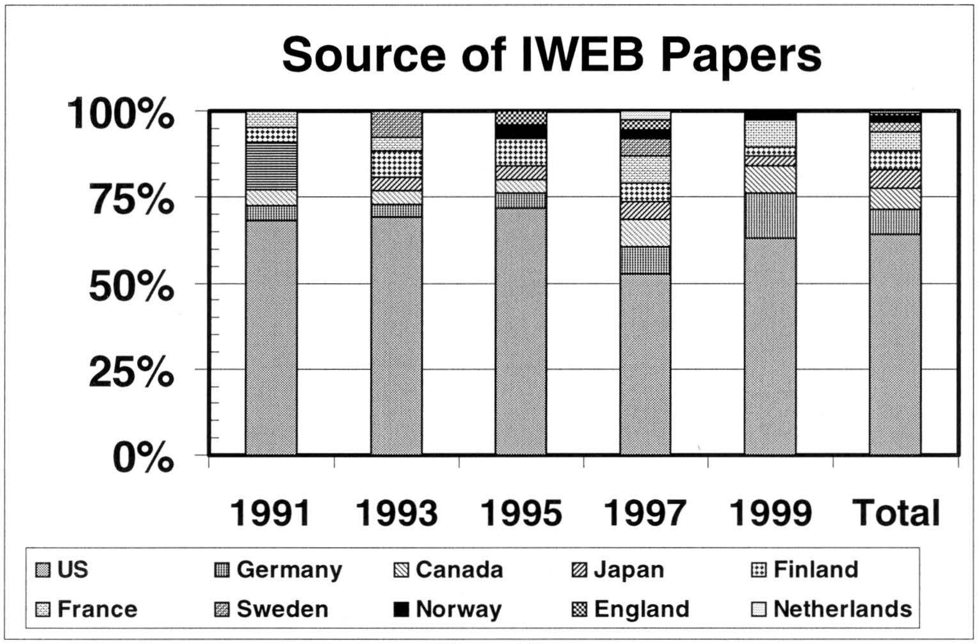

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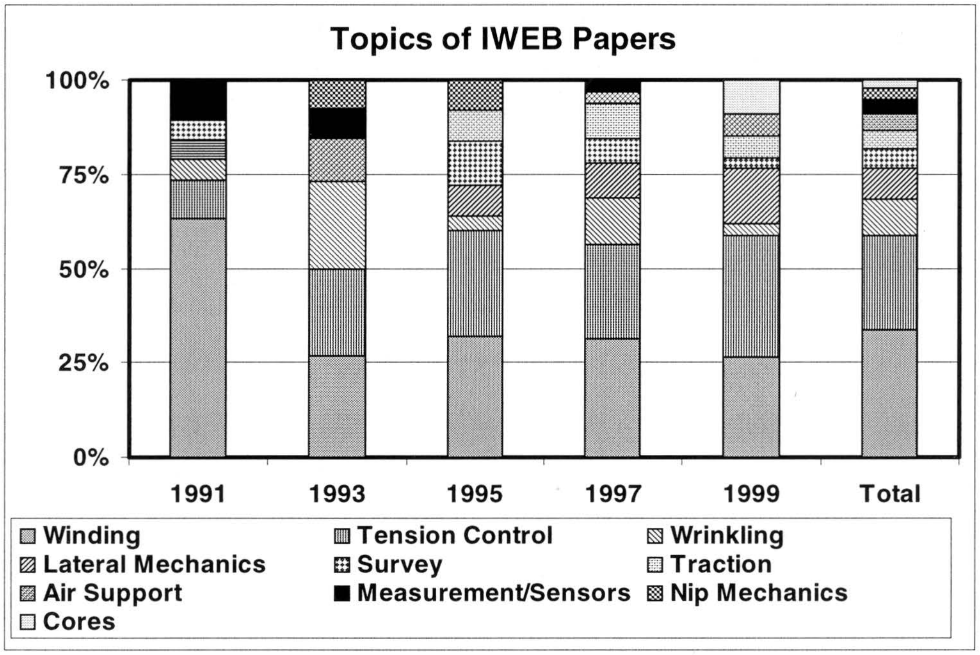

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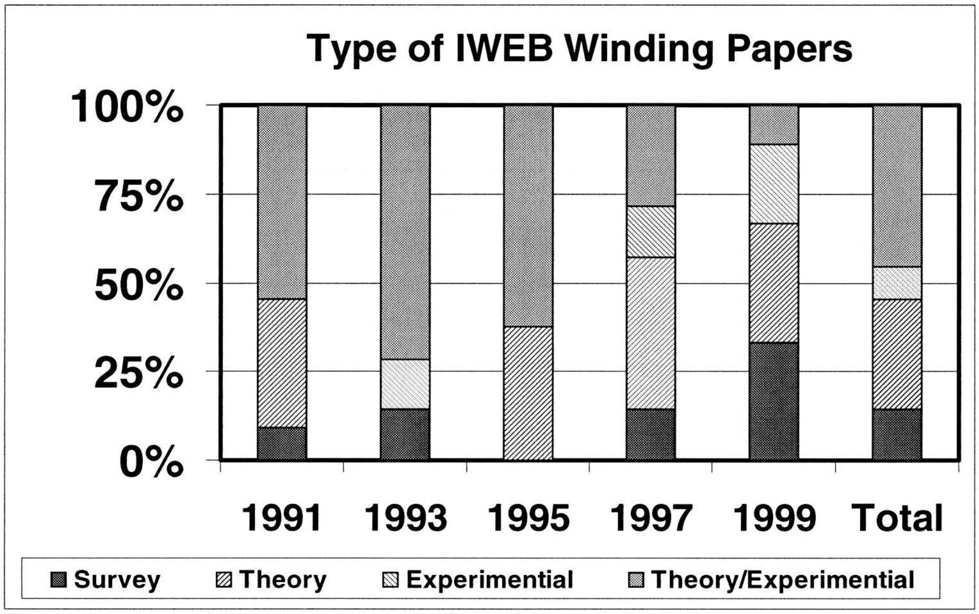

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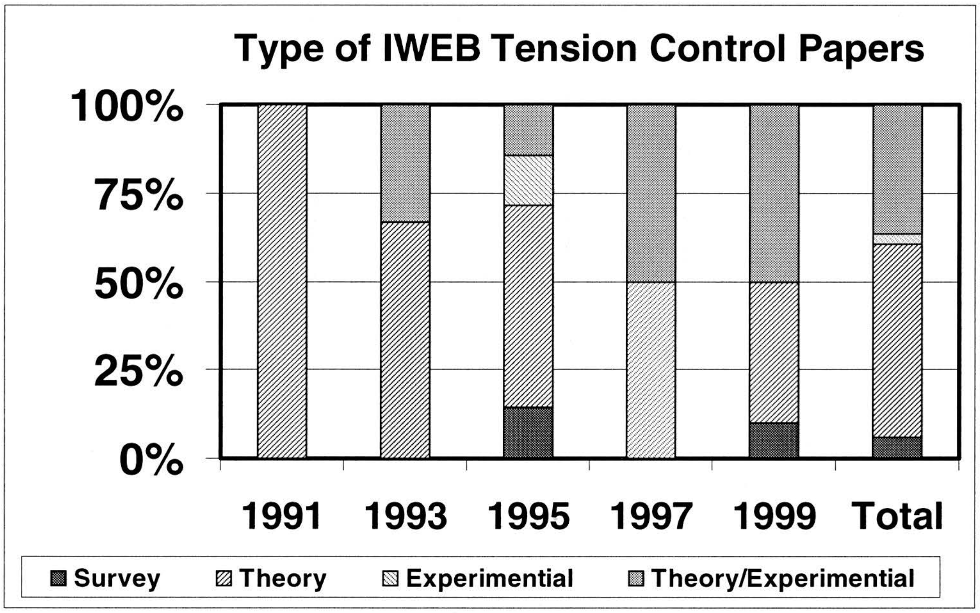

Figure (7)

WEB HANDLING TECHNOLOGY
COST-VALUE ANALYSIS

PLEASE RATE 1 – 10 (1=LOW, 10=HIGH)

Technology	**Cost (1-10)**	**Benefit (1-10)**
Winding		
Longitudinal Dynamics and Tension Control		
Wrinkling		
Lateral Mechanics		
Traction		
Air Support Conveyance		
Measurement/Sensors		
Air Entrainment		
Slitting		
Nip Mechanics		

Keynote Presentation – *Web Handling Technologies, Past, Present and Future*

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Name & Affiliation	**Question**
P. Bourgin – Ecole Supérieure de Plastirgic	I have one comment concerning your presentation of the evolution of technical knowledge, which from my point of view is quite interesting. It appears to be a linear process starting from common use and experimentation to theory. I think we should not ignore that many inventions occurred as jumps or breakthroughs. For instance, advances in communication were not the result of improving carrier pigeons. So now let us move on to the second comment I would like to make. I agree that Zig Hakiel's contribution was a major one in 1987. But still, I think it was an improvement of models that already existed and we should not ignore what I call precursor models. For instance the contributions of Tramposch, Altmann, Connolly and Winarski were really the breakthroughs. They used existing models like the Brown and Goodman model in 1963, which was proposed for the creation of planets. I think that is the real breakthrough. These models all relied upon the assumption of a constant radial modulus for the roll. Of course we all know the radial modulus is a function of the stress. Hakiel's contribution was substantial to introduce this dependence, but still he improved over the existing models. I don't want to enter into a controversy because which specific contributions were logical steps and which were breakthroughs was not the intent of my comment. But you see what I mean. I believe we need to focus on both the linear processes and then the real breakthroughs.
Name & Affiliation	**Comment**
R. Swanson – 3M	Yes, I agree with you. I was thinking that exact same thought as I was putting this talk together. I thought that you don't put a person on the moon by this linear progression. Then I started thinking about all the experimentation that went into rocketry. How long were they experimenting with rockets before they sent someone up to the moon? I still think, even as big a breakthrough as putting a person on the moon, there were lots of experiments. Theories were proposed and they did not match the experimental results. I think that there is a linear progression. In my mind, putting a man on the moon was the result of the linear progression.
Name & Affiliation	**Comment**
P. Bourgin – Ecole Supérieure de Plastirgic	I agree. Both the linear processes and breakthroughs will exist. They are supported by each other. I really believe that.

Name & Affiliation	Comment
J. Dobbs – 3M	I think an analogy to the previous discussion to where the breakthroughs occur is in electromagnetic theory where lots and lots of very good theory existed before Maxwell. But anyone who's ever studied electromagnetic theory acknowledges that Maxwell is the first person that puts it altogether in four equations. That is the breakthrough, taking all the parts and pieces, and the assembly of everything into a complete working theory that becomes a pivotal point for everything that follows.