ECT Modeling Topics

TAPPI CORBOTEC Annual Summer Meeting
Mystic Marriott Hotel & Spa, Groton, Connecticut

June 19, 2008

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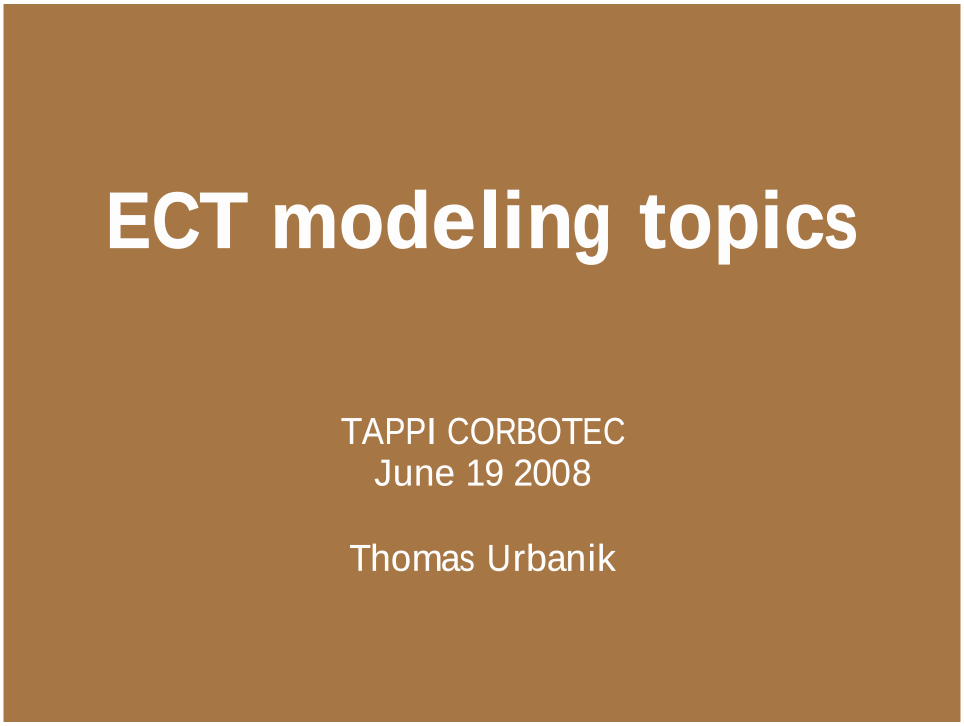

ECT modeling topics

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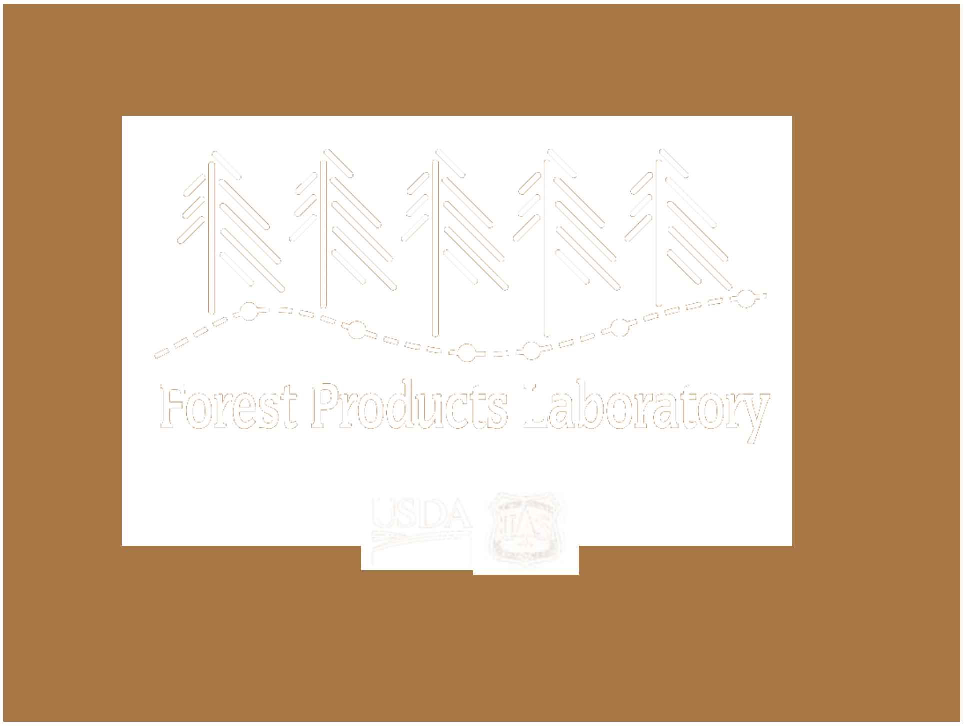
Thomas Urbanik

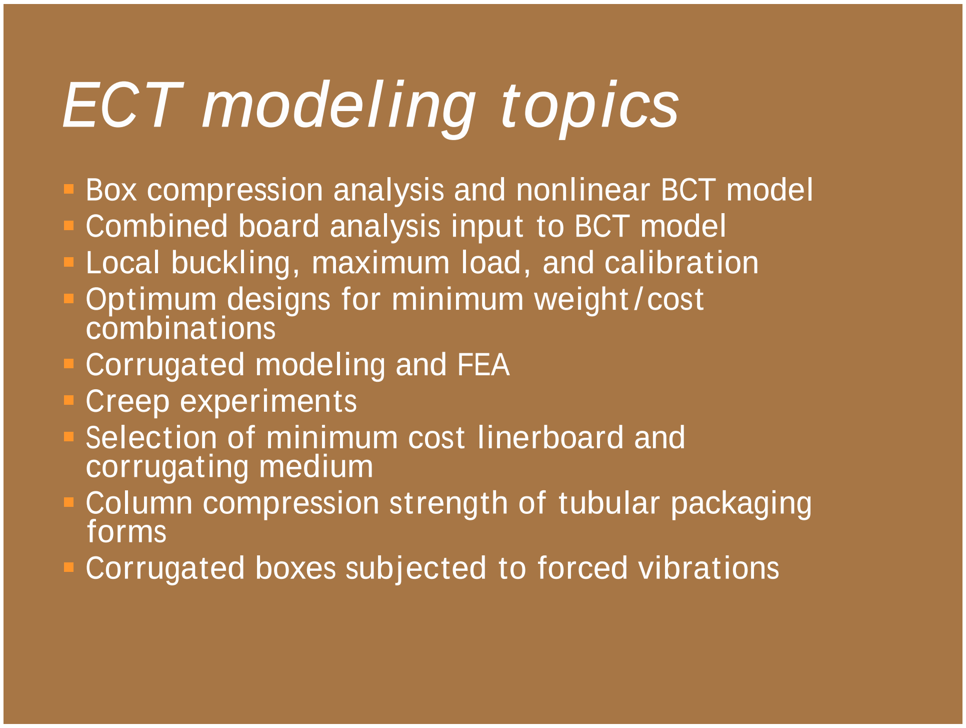
Figure 1.1—Research in the edgewise compression “test” strength (ECT) of corrugated fiberboard enables producers and users of corrugated board to relate the properties and cost of paperboard to the end-use performance of corrugated containers, commonly indicated by the box compression “test” strength (BCT).



Forest Products Laboratory

USDA

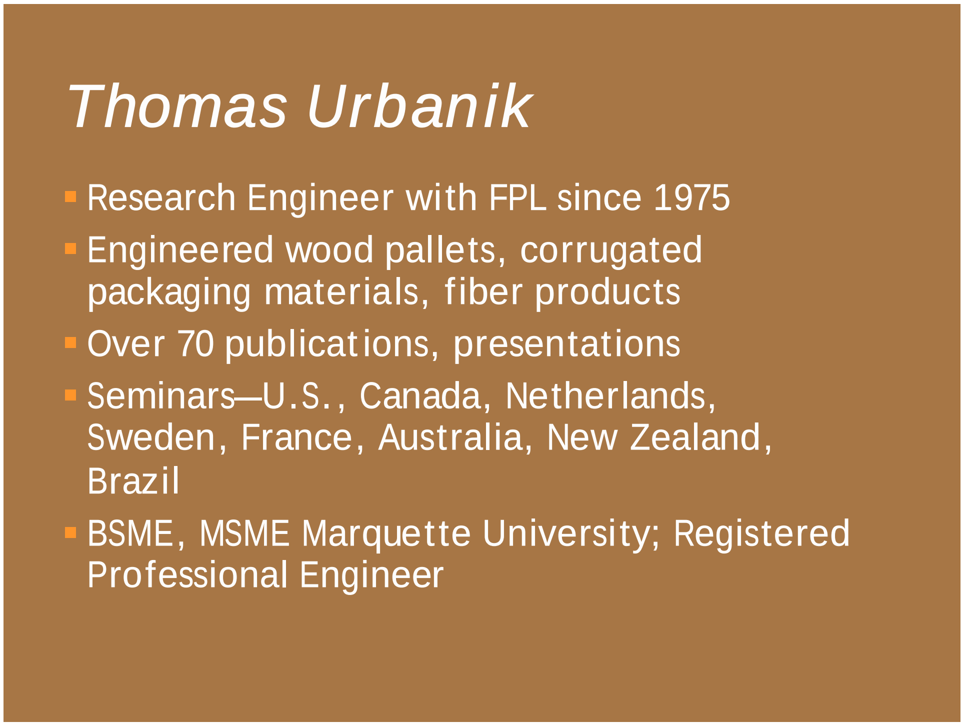
Figure 1.2—In service to the public, the Forest Products Laboratory (FPL) has conducted research in corrugated fiberboard that has been estimated to utilize 12 percent of fiber from forested lands.



ECT modeling topics

- Box compression analysis and nonlinear BCT model
- Combined board analysis input to BCT model
- Local buckling, maximum load, and calibration
- Optimum designs for minimum weight/cost combinations
- Corrugated modeling and FEA
- Creep experiments
- Selection of minimum cost linerboard and corrugating medium
- Column compression strength of tubular packaging forms
- Corrugated boxes subjected to forced vibrations

Figure 1.3—To understand box compression "test" strength (BCT) of corrugated containers, it is equally essential to understand ECT technology, nonlinear characterization of paper, process variables affecting paperboard cost, and the shipping and distribution environment.

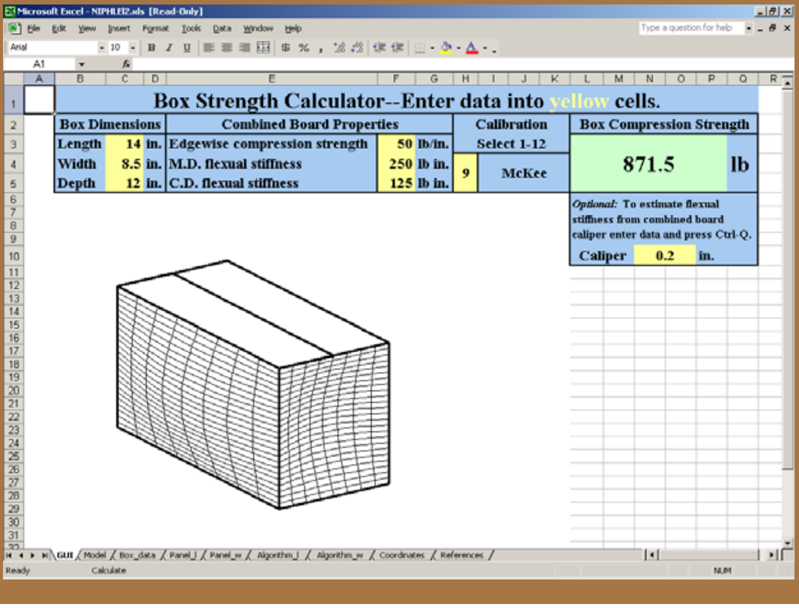


Thomas Urbanik

- Research Engineer with FPL since 1975
- Engineered wood pallets, corrugated packaging materials, fiber products
- Over 70 publications, presentations
- Seminars—U.S., Canada, Netherlands, Sweden, France, Australia, New Zealand, Brazil
- BSME, MSME Marquette University; Registered Professional Engineer

Figure 1.4—Summary of credentials of presenter Thomas Urbanik.

Box compression analysis and nonlinear BCT model



Box Strength Calculator--Enter data into yellow cells.

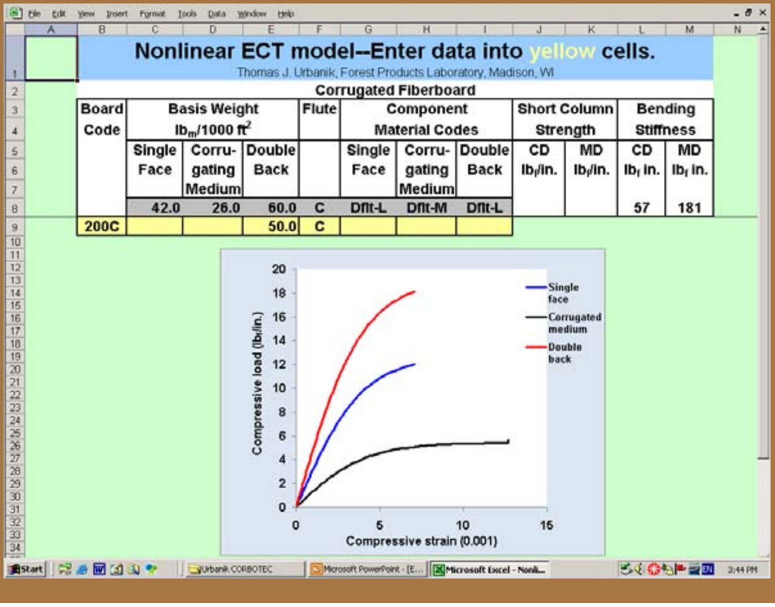
Box Dimensions			Combined Board Properties			Calibration Select 1-12		Box Compression Strength	
Length	14	in.	Edgewise compression strength	50	lb/in.				
Width	8.5	in.	M.D. flexual stiffness	250	lb in.	9	McKee	871.5	lb
Depth	12	in.	C.D. flexual stiffness	125	lb in.				

Optional: To estimate flexual stiffness from combined board caliper enter data and press Ctrl-Q.

Caliper 0.2 in.

Figure 1.5—Results of Urbanik and Saliklis (2004) were incorporated into an Excel spreadsheet by Urbanik (2004) for computing BCT in terms of combined board ECT, bending stiffness, and box geometry. The spreadsheet was awarded the Runner-Up status in the NIPHLE Computer Software Programs/System design competition.

Combined board analysis input to BCT model



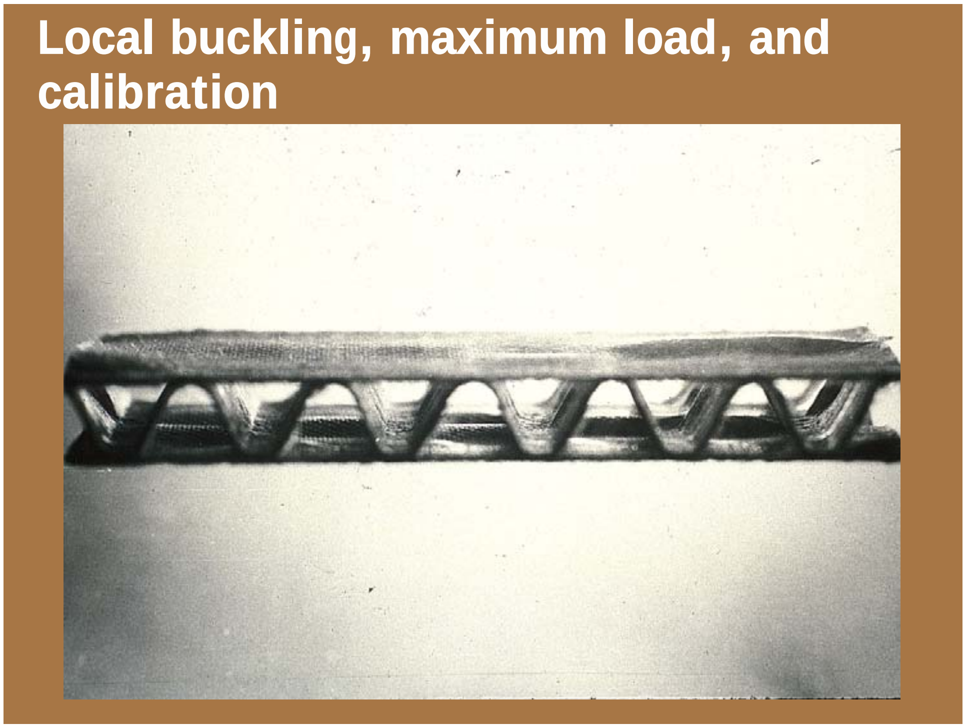
Nonlinear ECT model--Enter data into yellow cells.

Thomas J. Urbanik, Forest Products Laboratory, Madison, WI

Corrugated Fiberboard

Board Code	Basis Weight lb$_m$/1000 ft^2			Flute	Component Material Codes			Short Column Strength		Bending Stiffness	
	Single Face	Corru-gating Medium	Double Back		Single Face	Corru-gating Medium	Double Back	CD lb$_f$/in.	MD lb$_f$/in.	CD lb$_f$ in.	MD lb$_f$ in.
	42.0	26.0	60.0	C	Dflt-L	Dflt-M	Dflt-L			57	181
200C			50.0	C							

Figure 1.6—An ECT analysis spreadsheet under development will link with the BCT spreadsheet (Figure 1.5) and enable users to compute box strength from paper properties and corrugating variables. The calculated outputs of ECT and bending stiffness become inputs to the BCT spreadsheet (Figure 1.5).



Local buckling, maximum load, and calibration

Figure 1.7—DVD movie files of actual ECT local buckling can be accessed at http://www.corrugraphics.com/FTP.htm and navigating to files Title04.mpg through Title11.mpg.

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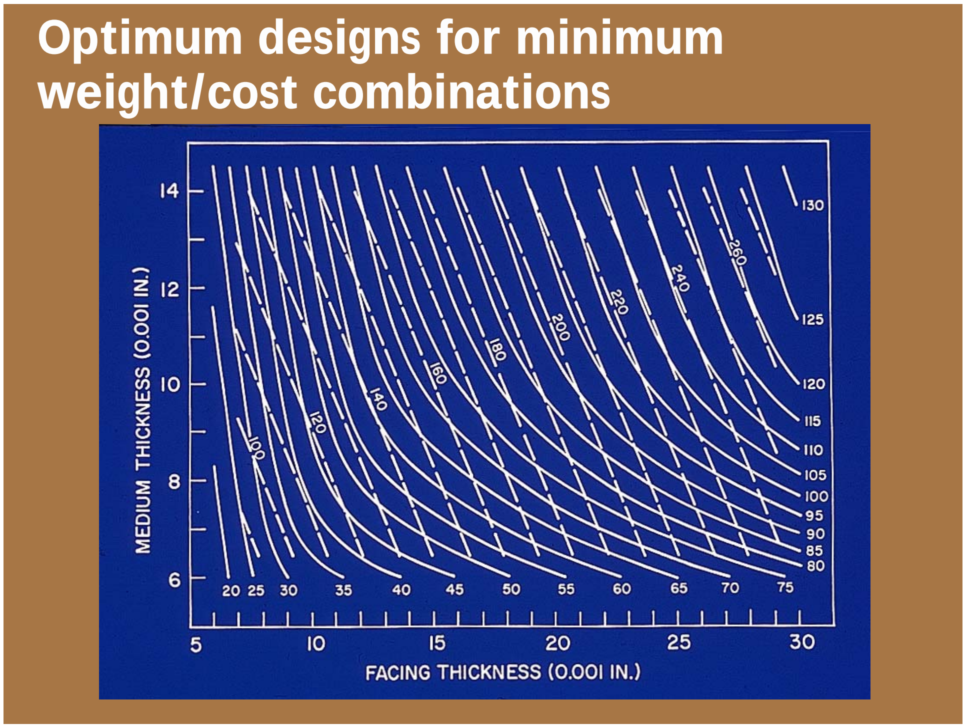
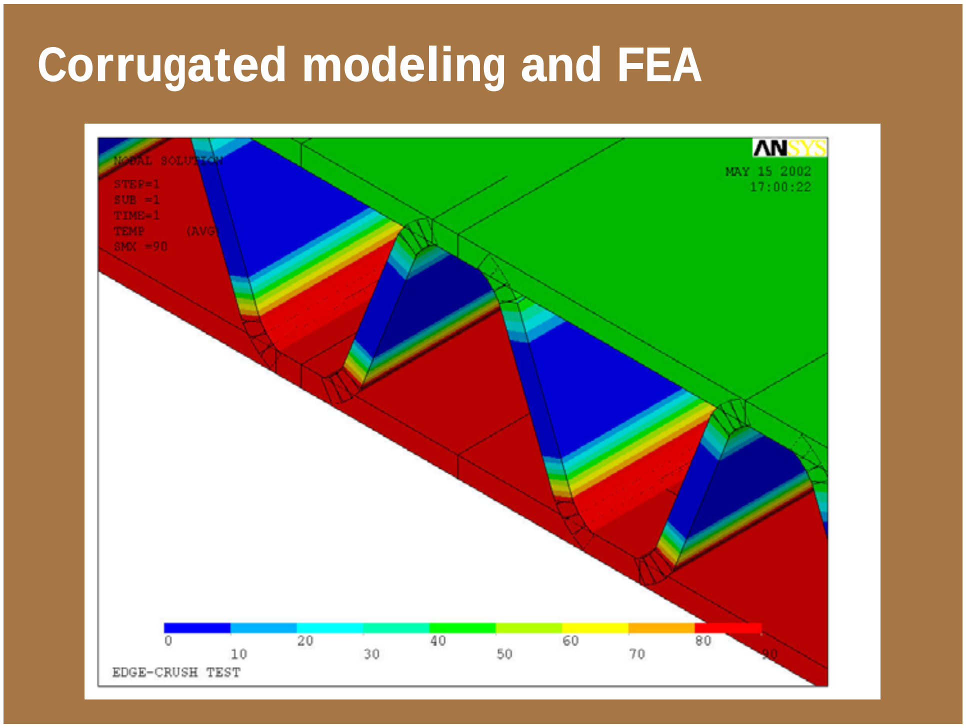


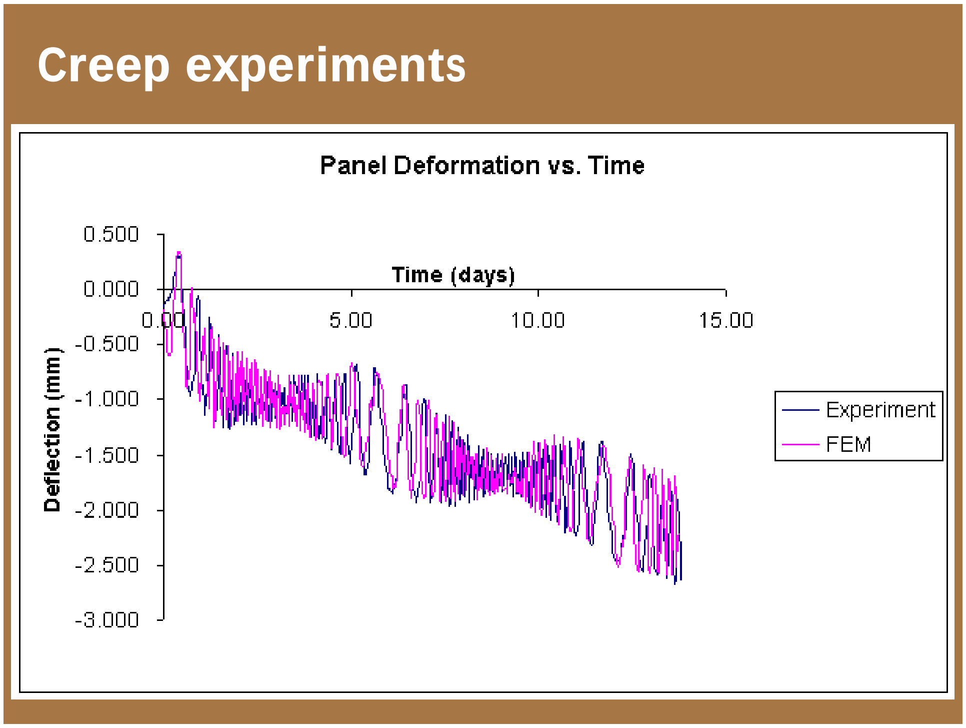
Optimum designs for minimum weight/cost combinations

Figure 1.8—Analyses by Johnson et al. (1979) and Ince and Urbanik (1985) have revealed the weight-savings and economic implications, respectively, of balancing the linerboard and corrugating medium properties so as to achieve an optimum design. Results enable corrugated board converters to determine the lowest cost combination of paperboards to produce their combined board grades. (Legend: combined board weight in lb/1000 ft^2—straight line contours; ECT in lb/in—curved contours)



Corrugated modeling and FEA

Figure 1.9—Studies by Urbanik and Saliklis (2003), Saliklis et al. (2003), and Rahman et al. (2006) uncovered the advantages and limitations of finite element software in box compression analysis. Finite element analysis can supplement costly experiments but is limited by necessary assumptions to satisfy intimate details regarding imperfections and attachments points.

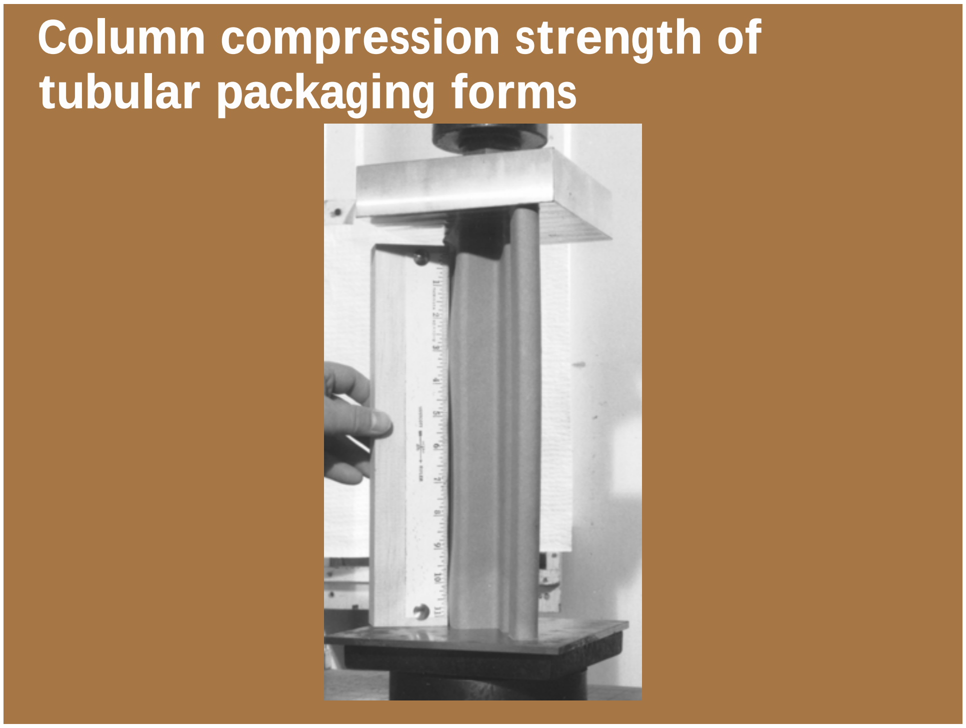


Creep experiments

Figure 1.10—Creep experiments by Urbanik and Lee (1995) and Urbanik (1998) provide novel criteria for understanding the combined effects of cyclic humidity and long-duration loading on strength of corrugated containers in real-world environments. Results enable researchers to design testing protocols most representative of actual environmental conditions.

Selection of minimum cost linerboard and corrugating medium

Figure 1.11—In a study by Urbanik and Won (2006), the FPL's experimental refiner was used to obtain a basic understanding of how the cost of refining energy compares to the cost of fiber in increasing paperboard strength.

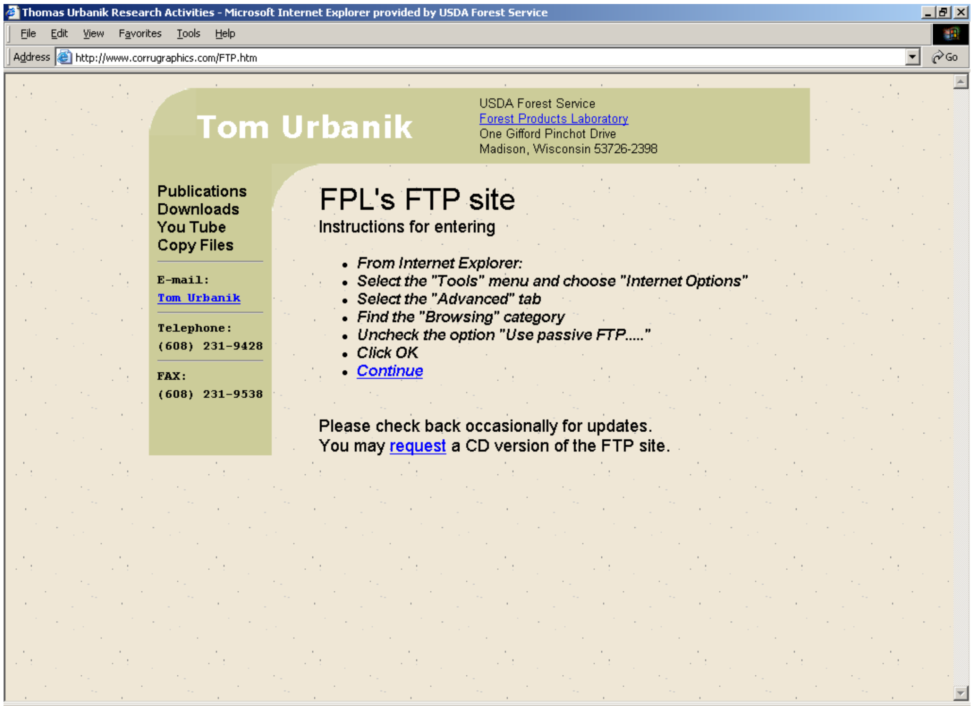


Column compression strength of tubular packaging forms

Figure 1.12—A study of corner posts was conducted by Urbanik et al. (2006) to understand the design principles of these packaging forms used to reinforce the strength of corrugated containers.

Corrugated boxes subjected to forced vibrations

Figure 1.13—In an apparent response to emerging economies, China and India have sought out FPL publications by Urbanik (1978, 1984) regarding effects of transportation vibration on unitized corrugated fiberboard containers.



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FPL's FTP site

Instructions for entering

- *From Internet Explorer:*
- *Select the "Tools" menu and choose "Internet Options"*
- *Select the "Advanced" tab*
- *Find the "Browsing" category*
- *Uncheck the option "Use passive FTP....."*
- *Click OK*
- *Continue*

Please check back occasionally for updates.
You may request a CD version of the FTP site.

Figure 1.14—The PowerPoint presentations, DVD movie files, and publications presented here can be downloaded in electronic format by going to the web site located at http://www.corrugraphics.com/FTP.htm and following the provided instructions.

Questions ?

Figure 1.15

References

Ince, P.J., and T.J. Urbanik. 1986. Economics of fiber cost and compressive strength of singlewall-wall corrugated boxes. Tappi Journal, October:102-105.

Johnson, M.W., Jr., T.J. Urbanik, and W.E. Denniston. 1979. Optimum fiber distribution in singlewall corrugated fiberboard. United States Department of Agriculture, Forest Service, Forest Products Laboratory Research Paper FPL 348.

Rahman, A.A., T.J. Urbanik, and M. Mahamid. 2006. FE analysis of creep and hygroexpansion response of corrugated fiberboard to a moisture flow: A transient nonlinear analysis. Wood and Fiber Science 38(2):268-267.

Saliklis, E.P., T.J. Urbanik, and B. Tokyay. 2003. Bilinear modeling of cellulosic orthotropic nonlinear materials. Journal of Pulp and Paper Science 29(12):407-411.

Urbanik, T.J. 1978. Transportation vibration effects on unitized corrugated containers. United States Department of Agriculture, Forest Service, Forest Products Laboratory, Madison, WI, Research Paper FPL 322.

Urbanik, T.J. 1984. Vibrational loading mechanism of unitized corrugated containers with cushions and non-load bearing contents. The Shock and Vibration Bulletin, Part 3, Structural Dynamics, Machinery Dynamics and Vibration Problems, The Shock and Vibration Information Center, Naval Research Laboratory, Washington, D.C., June, pp: 111-122.

Urbanik, T.J. 1998. Strength criterion for corrugated fiberboard under long-term stress. Tappi Journal 81(3):33-37.

Urbanik, T.J. 2004. Nonlinear BCT Model. National Institute of Packaging Handling and Logistic Engineers (NIPHLE) Conference, Camp Hill, PA, May.

Urbanik, T.J., and S.K. Lee. 1995. Swept sine humidity schedule for testing cycle period effects on creep. Wood and Fiber Science 27(l):68-78.

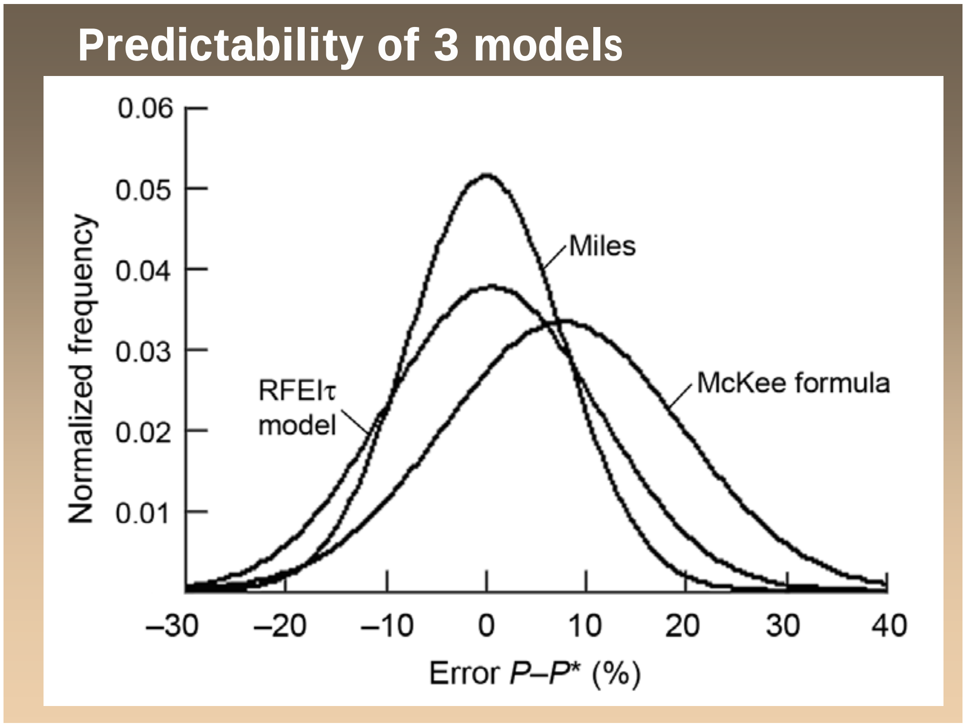
Urbanik, T.J., and E.P. Saliklis. 2003. Finite element corroboration of buckling phenomena observed in corrugated boxes. Wood and Fiber Science 35(3):322-333.

Urbanik, T.J., and J.M. Won. 2006. Principles of minimum cost refining for optimum linerboard strength. Progress in Paper Recycling 15(4):13-21.

Urbanik, T.J., S.K. Lee, and C.G. Johnson. 2006. Column compression strength of tubular packaging forms made from paper. ASTM Journal of Testing and Evaluation 34(6):1-7.

Box Compression Analysis of World Wide Data Spanning 46 Years

Figure 2.1—Advanced analysis techniques have been incorporated within an improved box compression model that preserves the principles of previous models but removes the constraints imposes by computing limitations at the time of development.



Predictability of 3 models

Figure 2.2—Frequency distributions, normalized to have areas equal to 1, for three model and data combinations from Urbanik and Frank (2006). Legends refer to the Miles (1966) interlaboratory data reproducibility, the formula of McKee et al. (1963), and the improved single wall model of the 2006 report.

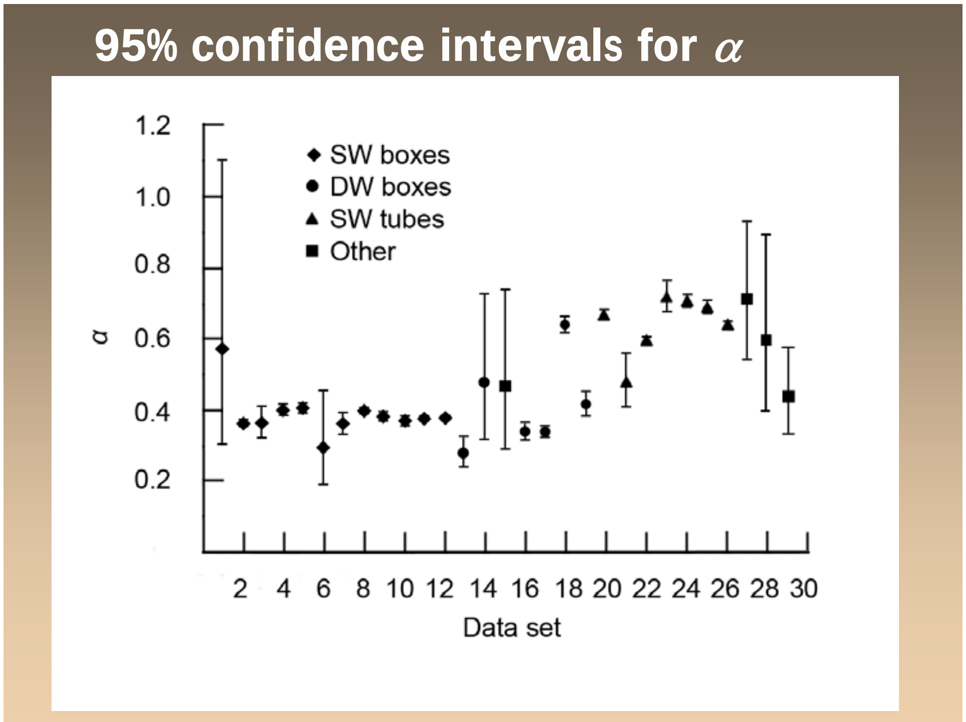


Figure 2.3—Approximate 95% confidence intervals determined for parameter α, believed to be related to the horizontal score-line effect on strength, in the improved box compression model. Most data sets with single-wall boxes are observed to be statistically indistinguishable.

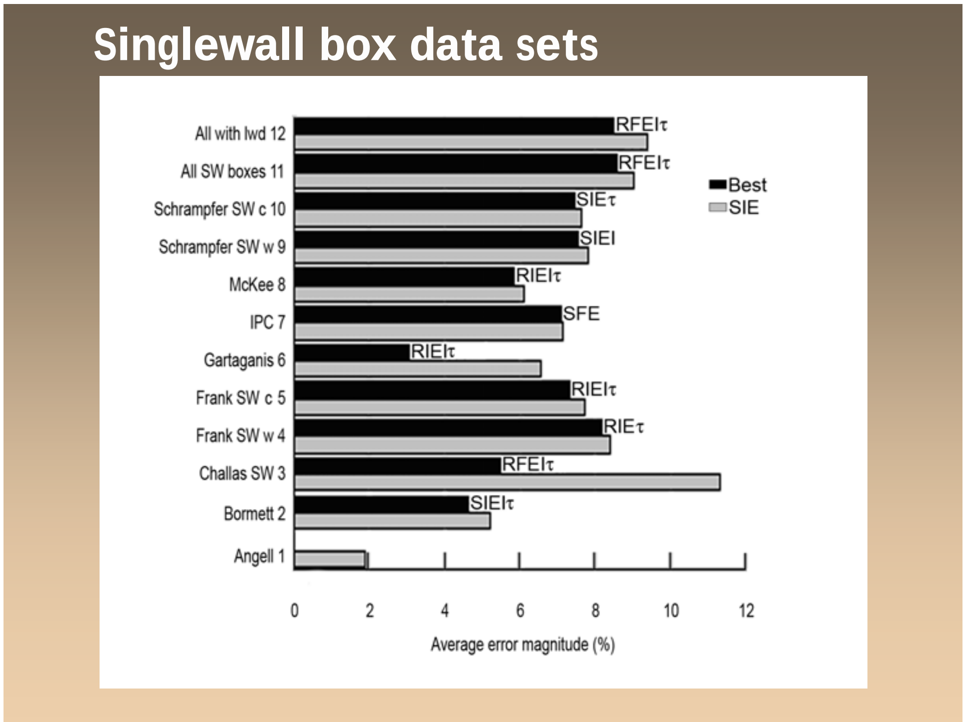
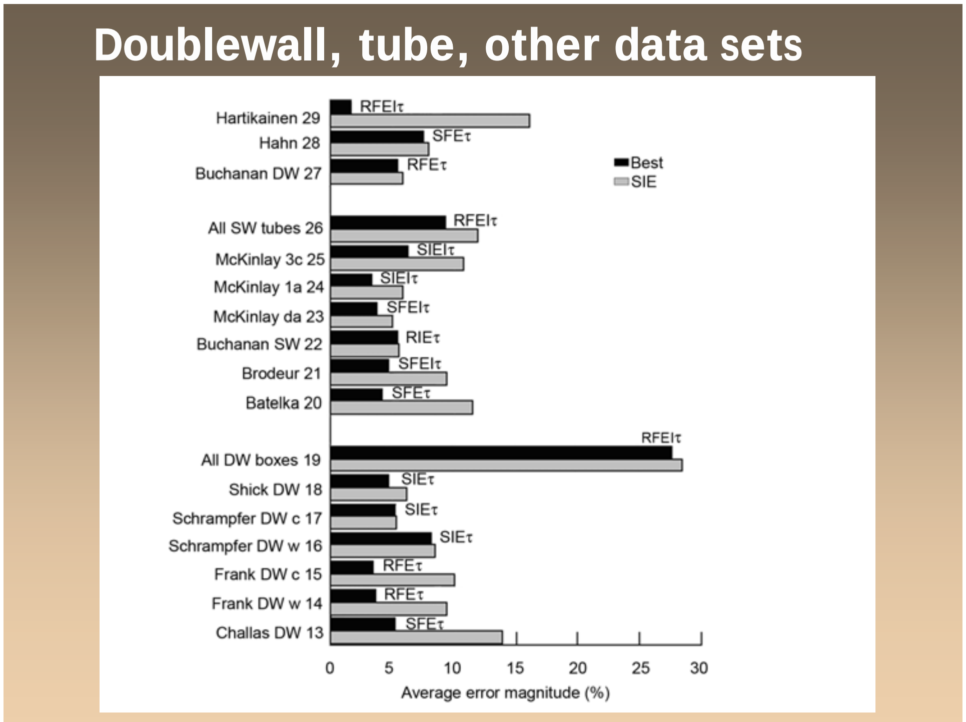
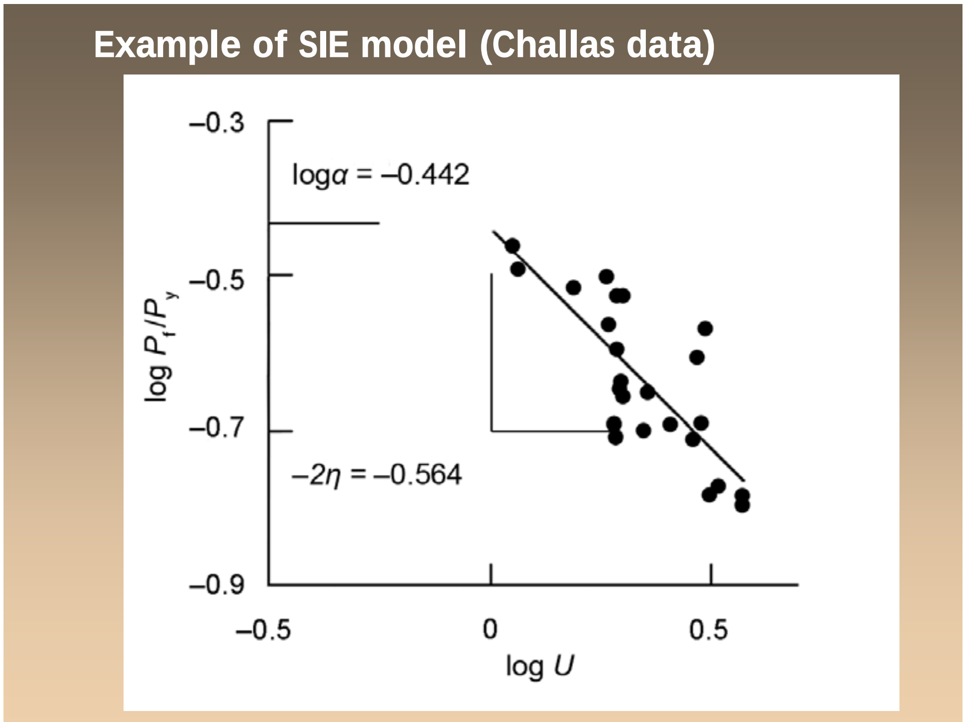


Figure 2.4—Average error magnitudes between predictions and data determined for best of 16 models applied to single-wall box data sets in report by Urbanik and Frank (2006). The definitions of the legends representing various models are explained in the 2006 report.



Doublewall, tube, other data sets

Figure 2.5—For comparison with single-wall data (Figure 2.4), double-wall box data sets and tube data sets by Urbanik and Frank (2006) were also analyzed and found to exhibit greater variability (Figure 2.3).



Example of SIE model (Challas data)

Figure 2.6—Calibration of model to single-wall box compression data by Challas et al. (1994) assuming only an elastic mode of buckling failure.

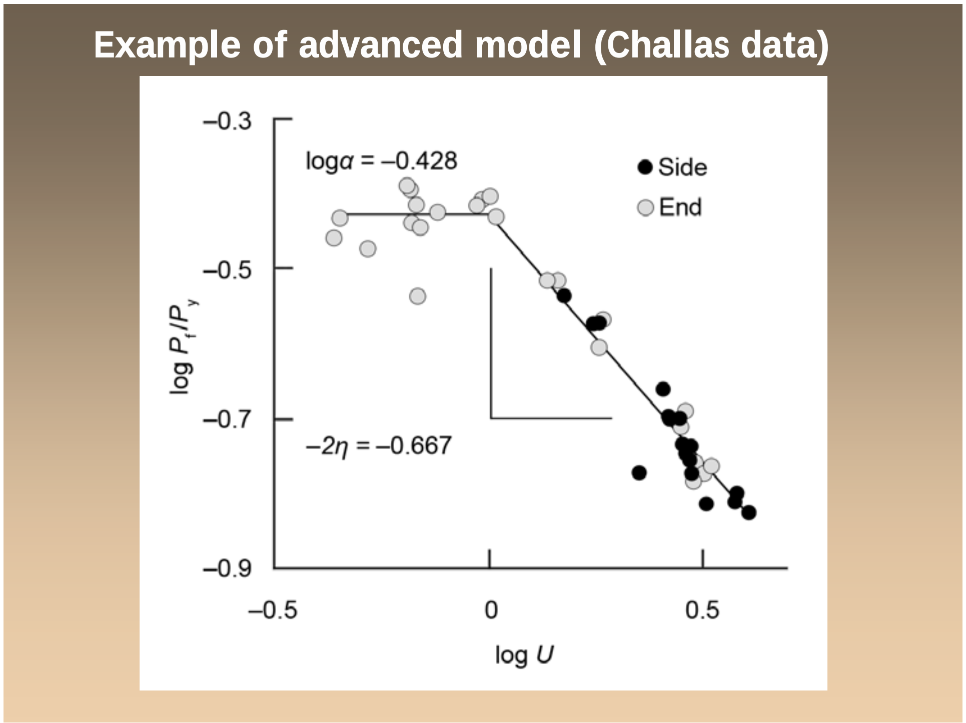

Example of advanced model (Challas data)

Figure 2.7—Calibration of model to single-wall box compression data by Challas et al. (1994) assuming a combination of elastic and inelastic modes of buckling failure. Results of various model calibrations (Figure 2.6) quantify the best combinations of square S or rectangular R geometry, infinite I or finite F depth, elastic E or combined elastic and inelastic EI failure mode, and mode shape correction τ assumed to apply.

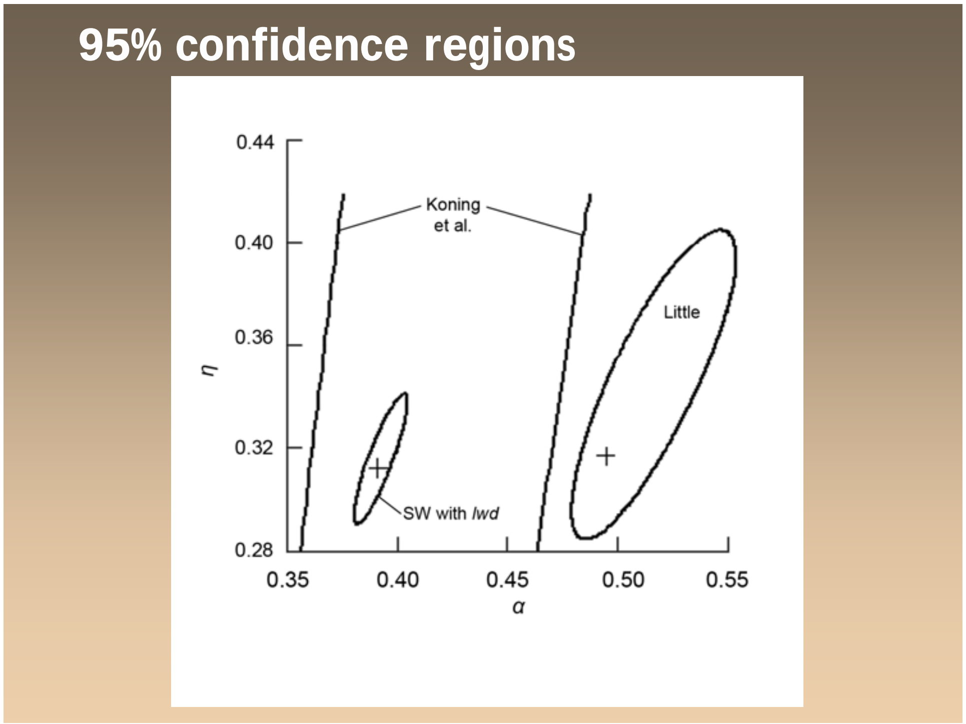

95% confidence regions

Figure 2.8—95% joint confidence regions for model parameters in improved box compression model applied to single-wall (SW) data with length, width, and depth (lwd) dimensions and compared with data sets by Koning and Moody (1969) and Little (1943). A quantification of the joint confidence region lacking from previously reported models helps to interpret the interactions among model parameters.

Questions ?

Figure 2.9

References

Challas, J., M. Schaepe, and C.N. Smith. 1994. Predicting package compression strength geometry effect. IPST Project 3806, final report. Institute of Paper Science and Technology, Georgia Tech, Atlanta, GA.

Koning, J.W., Jr,. and R.C. Moody. 1969. Effect of glue skips on compressive strength of corrugated fiberboard containers. Tappi J. 52(10):1910–15.

Little, J.R. 1943. A theory of box compressive resistance in relation to the structural properties of corrugated paperboard. Paper Trade J. 116(24):31–34.

McKee, R.C., J.W. Gander, and J.R. Wachuta. 1963. Compression strength formula for corrugated boxes. Paperboard Packaging, August:149–159.

Miles, J.G. 1966. Compressive strength of corrugated containers: An interlaboratory study. Mater. Res. Standards, March:142–146.

Urbanik, T.J., and B. Frank. 2006. Box compression analysis of world-wide data spanning 46 years. Wood Fiber Sci. 38(3):399-416.

Examples of buckling patterns

Figure 3.1—Buckling patterns observed in a variety of fiber-based structures (experimental and theoretical) prior to actual failure illustrate the buckling load that is input to an empirical postbuckling strength model.

Intermediate corrugated container

Figure 3.2—Buckling pattern with one wave developing along the side of a corrugated container subjected to top-to-bottom compression.

Figure 3.3—Buckling pattern with multiple waves developing along the side of a corrugated container subjected to top-to-bottom compression.

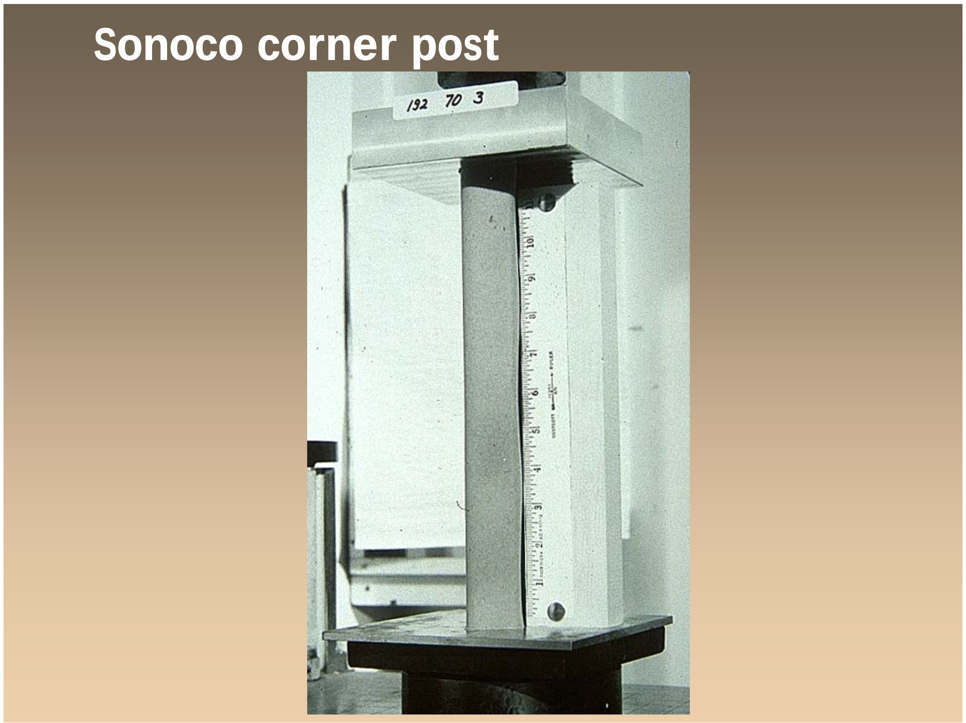


Figure 3.4—Local buckling pattern along the surface of a tubular packaging form subjected to column compression in a study by Urbanik et al. (2006).

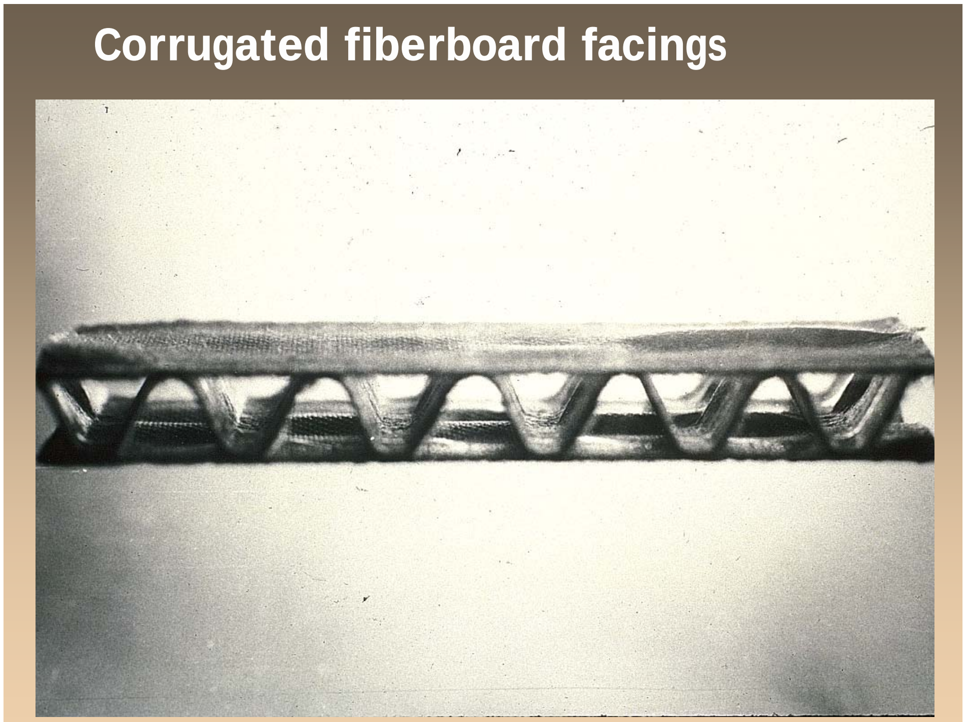


Figure 3.5—Localized buckling in a short column specimen of corrugated fiberboard with a camera view through the flutes. Actual specimen orientation and applied load are the same as in a conventional edgewise crush test. Here the viewable image is tilted. With lightweight facings relative to the corrugated medium, the facings buckle first. Additional views in response to other load levels are given by Urbanik (1990).

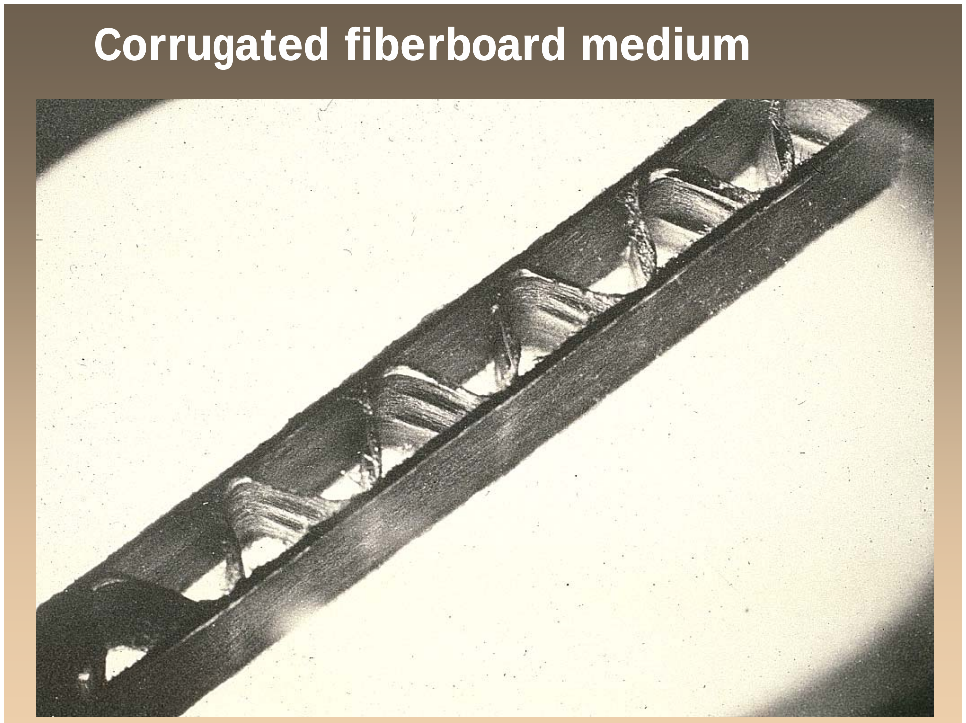
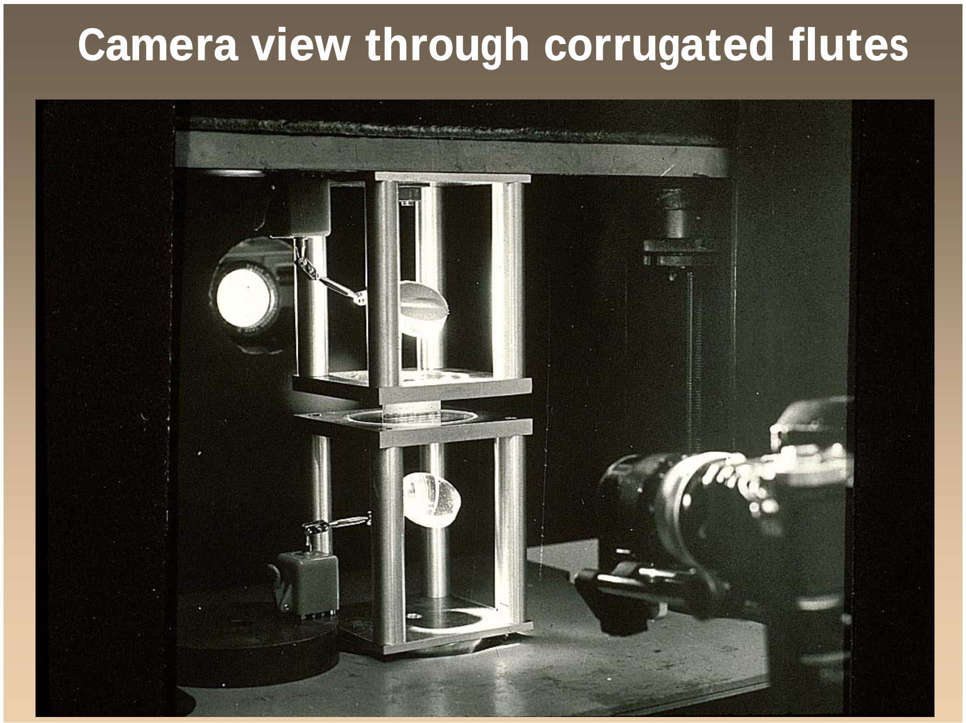
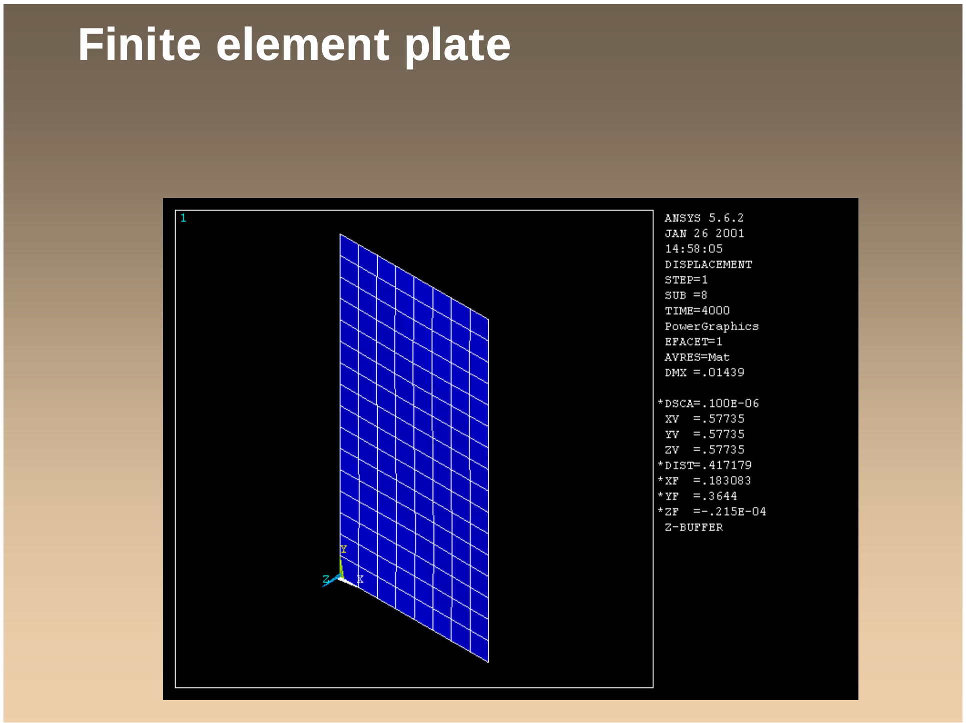


Figure 3.6—Localized buckling in a short column specimen of corrugated fiberboard with a camera view through the flutes. With a lightweight corrugated medium relative to the facings, the core buckles first. Additional views in response to other load levels are given by Urbanik (1990).



Camera view through corrugated flutes

Figure 3.7—An edge crush specimen of corrugated fiberboard loaded between two glass platens in combination with light and mirrors enabling a camera view through the flutes. A second camera captures the simultaneous load-deformation curve from a chart recorder (not seen).



Finite element plate

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*YF  =.3644
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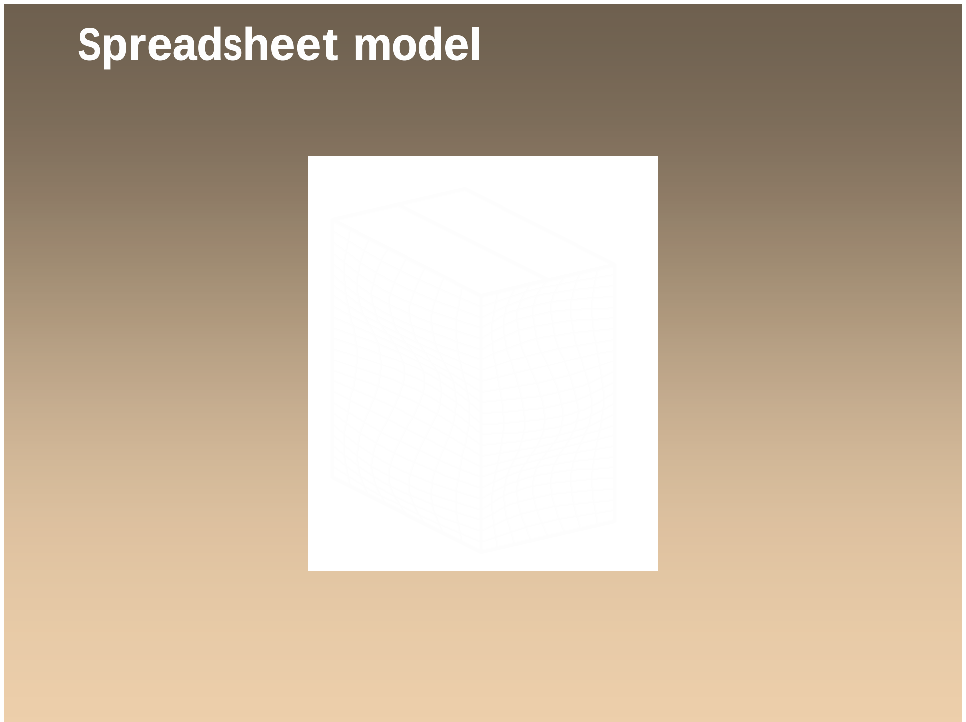
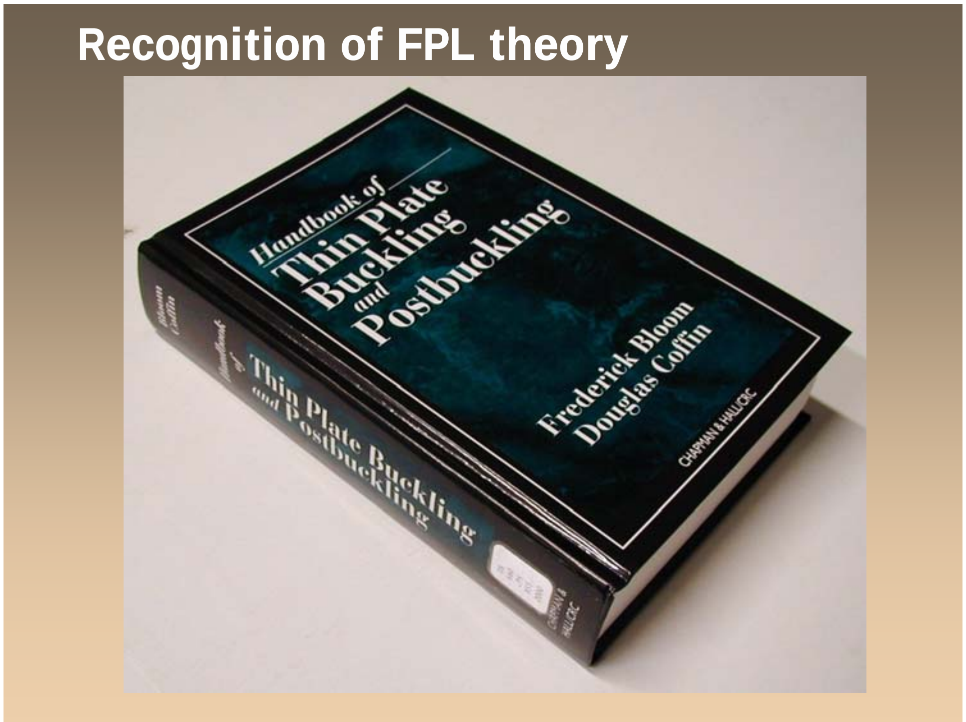
Figure 3.8—Finite element plate examined for buckling in a parametric design by Urbanik and Saliklis (2003). Video of actual plate buckling can be accessed at http://www.corrugraphics.com/FTP.htm and navigating to file FILES2.AVI.



Spreadsheet model

Figure 3.9—Buckling mode of corrugated container from example inputs to spreadsheet model by Urbanik (2004). Spreadsheet is obtainable at http://www.corrugraphics.com/FTP.htm and navigating to file Nonlinear_BCT_Model.xls.



Recognition of FPL theory

Figure 3.10—Handbook by Bloom and Coffin (2001) further discusses the Johnson and Urbanik (1984) generalization of the von Karmen Equations for plates exhibiting nonlinear elastic behavior.

Questions ?

Figure 3.11

References

Bloom, F., and D. Coffin. 2001. Handbook of thin plate buckling and postbuckling. Chapman & Hall/CRC.

Johnson, M.J., Jr., and T.J. Urbanik. 1984. A nonlinear theory for elastic plates with application to characterizing paper properties. Journal of Applied Mechanics 51(3):146-152.

Urbanik, T.J. 1990. Correcting for instrumentation with corrugated fiberboard edgewise crush test theory. Tappi Journal, October:94, 263-268.

Urbanik, T.J. 2004. Nonlinear BCT Model. National Institute of Packaging Handling and Logistic Engineers (NIPHLE) Conference, Camp Hill, PA, May.

Urbanik, T.J.,and E.P. Saliklis. 2003. Finite element corroboration of buckling phenomena observed in corrugated boxes. Wood and Fiber Science 35(3):322-333.

Urbanik, T.J., S.K. Lee, and C.G. Johnson. 2006. Column compression strength of tubular packaging forms made from paper. ASTM Journal of Testing and Evaluation 34(6), November:1-7.