Automated Box Buckling Strength Analyses with Finite Element Modeling

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Abstract. Finite element analysis (FEA) provides valuable information for buckling/stacking analyses of corrugated boxes. However, FEA requires time consuming custom geometric analysis and specialized structural engineering personnel with background in modeling of nonlinear anisotropic viscoelastic material like paper products. This research studies a systematic approach by which simple geometric and paper properties are input and buckling strength/deformed box shapes are output. All the analyses will be conducted in a FEA software (ABAQUS) including geometric modeling and auto-meshing, material nonlinear anisotropic homogenization of corrugated board, and automated outputs. The systematic approach provides a rapid analyses tool for non-specialized personnel to achieve accurate buckling/stacking analysis of corrugated box.

Keywords: Corrugated board buckling strength · Auto-meshing algorithm · Homogenization · Finite element modeling

1 Introduction

Corrugated boxes are widely used in food packaging, horticulture packaging, electronics packaging, daily necessities packaging and other industry packaging etc. [1, 2] because of various attributes including low cost, high versatility, easy handling process, and short recycle period etc. [3]. However, mechanical behavior of the corrugated paperboard is complex due to its time dependent characteristics with reference to manufacturing, moisture dependence, load, and temperature etc. [4, 5]. Thus, extensive and time consuming analyses and experiments are needed to design corrugated boxes against environmental impact and loadings such as compression during stacking, vibration during transportation, impact, temperature and moisture effects etc. [6–10] especially for expensive and/or fragile products like eggs, fruit, and electronics, etc. However, most packaging outfits lack the expensive/complicated equipment for extensive experiments and/or lack specialized personnel (e.g. structural engineers) for

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the analyses of the corrugated boxes. This leads to a lack of understanding and/or analyses of corrugated boxes against environmental impact and loadings, and eventually leads to damage of the corrugated boxes during transportation, stacking, and handling process etc. Thus, there is a great need for developing an easy and accurate approach for non-specialized personnel/company to conduct the performance analyses of the corrugated boxes.

This paper will first give a brief introduction of the traditional method being used for analyses of corrugated boxes and then a new computational framework will be introduced for providing efficient and accurate analyses of corrugated boxes with easy interface.

2 Traditional Method for Analyzing Corrugated Boxes

Traditional methods for analyzing the strength and failure of corrugated boxes include experiments, analytical models, and computational software. A thorough detailed introduction of these methods was previously discussed by Frank [11].

Experiments are the most direct way to analyze corrugated boxes. They provide strength, failure modes, and stress and strain information etc. of the corrugated boxes. However, professional personnel with structural engineering expertise are needed to analyze complexed geometry and complicated material properties of the paper in addition to expensive equipment (such as Universal Material Testing Systems and environmental chambers) and time consuming test cycle needed for the test.

Several researchers have developed analytical models [12–18] for analyses of corrugated box such as the McKee equation. These are semi empirical models for box buckling analyses which require heavy and costly experimentation through fabrication and testing of ECT, bending, and box specimens for model calibration. Urbanik and Frank later developed the Generalized McKee Equation. However, all these analytical models are limited to vertically loaded regular slotted containers (RSC). These model are not suitable for boxes with other styles and loading conditions.

Commercial software [19–22] based on these models were also developed to predict box compression strength or stacking strength. The models are easy to implement and thus widely used in industry. However, only a limited number of them can predict box performance based on paper properties [12, 14, 21, 22], so extra characterization of corrugated boards such as edge crush tests (ECTs) have to be conducted before using the models. Also, they are limited to a specific box type such as tubes [13] or regular slotted containers (RSCs) [14, 21]. Furthermore, box features such as slots as often seen in vented fruit box or inserts are difficult to be accounted for in these models.

3 Proposed Computing Framework

The objective of this computing framework is to provide a general analyses tool for efficient and accurate analyses of corrugated boxes with cloud computing option. This framework includes four modules named geometry module, material module, boundary/loading module and analysis module. Users only need to define the geometry of the box (length, width, height, folds, cut-outs, scoring, and staples information etc.), material property of the paper (liner and medium paper properties) and to specify the output results needed (BCT, failure or yield zones, stress fields, load vs. displacement, etc.) in the user interface page. The job will be submitted to and conducted in a computing platform through a cloud computing option and the output (BCT, Stacking strength, etc.) report will be sent back to users after the job is done.

Finite element analyses of the corrugated boxes will be conducted in ABAQUS including: automeshing of CAD model, automatic FEA model construction (including: material homogenization of the paper, boundary application, etc.), and nonlinear analysis of corrugated boxes. Riks method with imperfections is used in nonlinear analysis for prediction of buckling mode for corrugated boxes as shown in Fig. 1. The buckling modes of the box are obtained by Eigen mode buckling analysis and then the linear combination of the buckling modes with a scaling factor is used as imperfections for the nonlinear Riks analysis. Since model convergence is not guaranteed for a particular analysis, a convergence analysis is conducted with various levels of imperfection to automatically determine the BCT.

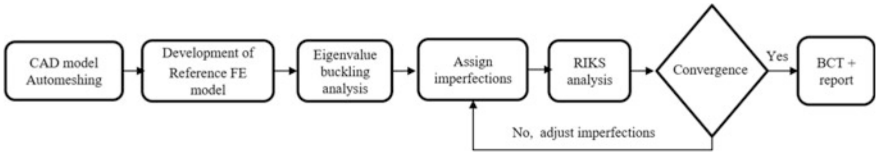

Fig. 1. Nonlinear analysis using Riks method with imperfections

Compared with analytical/empirical models and commercial software, the framework developed in this study has the advantages of (1) predicting box performance based on paper properties; (2) for different box types including RSC, EFOL, TFOL etc.; (3) with special design features such as scores, hand holds, ventilation holes, staples, etc. Compared with traditional finite element models, this framework has the advantage of predicting BCT for different box types without the requirement of professional structural engineers.

4 Case Study and Experimental Validations

For demonstration, three corrugated boxes with different box types (RSC, TFOL, and EFOL), sizes, corrugated board combinations, fluting types and relative humidity were modeled for the maximum box compression test strength values (BCT) predictions and compared with experimental results. Details of the boxes are shown in Table 1. These corrugated boxes were first conditioned (ASTM D685), and then kept in humidity chamber for 72 h under a set humidity level, and then compression tested (ASTM D642-15) in a Material Testing System (MTS) with a floating upper compression platen and fixed lower platen.

Table 1. Information of the corrugated boxes being analyzed

Box model	Outer dimension (mm)	Liner-medium-liner basis weight combination (g/m^2)	Fluting	Relative humidity (%)	Number of specimens
RSC	304.8 × 304.8 × 304.8	66.6-38.5-66.6	C	50	2
TFOL	673.1 × 198.4 × 320.5	51.8-48.8-51.8	B	85	4
EFOL	282.4 × 236.5 × 487.4	62.2-59.2-82.9	B	65	3

BCT from FE predictions and experiment are shown in Fig. 2. The prediction error varies from 3.6 to 14.4% for different boxes. The error for EFOL is larger than that of RSC and TFOL, and this is likely because of more details including hand holds and staples that are simulated in the FE models of EFOL. These details largely affect the side panel bending stiffness since 4 panels are partially bonded with the staples and with the stress concentration of the hand holds, these accumulate errors in the simulations.

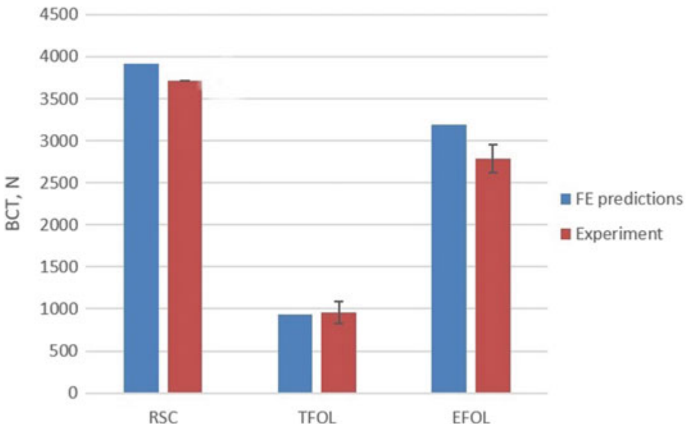

Fig. 2. Model predictions and experimental results for box BCT of 3 different box types. Note that the error bar for RSC's are not shown due to limited number of samples tested

5 Conclusions

This paper gives a brief introduction of the analysis methods of corrugated boxes and discusses the pros and cons of these approaches. Then, a new efficient and accurate computing framework is proposed with a cloud computing option for users without specialized background in structural/material/mechanical engineering. Users can easily define the inputs, and the job will be sent to the platform through the cloud computing option. Finite element models of corrugated boxes will be generated automatically in ABAQUS and the analyses will be done automatically. The report will be sent back to the users automatically after the job is done. This framework can analyze corrugated boxes (1) with different sizes; (2) with different box types and geometries; (3) with material property directly from paper; (4) rapidly with acceptable accuracy; (5) without the need for specialized personnel (e.g. structural engineers). Thus, this framework enables users/packaging companies to optimize the design/logistics of the corrugated boxes rapidly and cost effectively as compared with other approaches available in the literature and/or market.

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References

1. Chamberlian, D., & Kirwan, M. J. (2013). Paper and paperboard-raw materials. In *Processing and Properties. Handbook of Paper and Paperboard Packaging Technology*. New York: Wiley, Ltd.
2. Opara, U. L., & Mditshwa, A. (2013). A review on the role of packaging in securing food system: Adding value to food products and reducing losses and waste. *African Journal of Agricultural Research, 8,* 2621–2630.
3. Kaushal, M. C., Sirohiya, V. K., & Rathore, R. K. (2015). Corrugated board structure: A review. *International Journal of Application of Engineering and Technology, 2,* 228–234.
4. Haslach, H. W. (2009). Time-dependent mechanisms in fracture of paper. *Mechanics of Time-dependent Materials, 13,* 11–35.
5. Johnson, S., & Popil, R. (2015). Corrugated board bonding defect visualization and characterization. *International Journal of Adhesion and Adhesives, 59,* 105–114.
6. Fadiji, T., Berry, T. M., Coetzee, C. J., & Opara, U. L. (2018). Mechanical design and performance testing of corrugated paperboard packaging for the postharvest handling of horticultural produce. *Biosystems Engineering, 171,* 220–244.
7. Pascall, M. A. (2010). *Packaging for fresh vegetables and vegetable products. Handbook of vegetables and vegetable processing*. Oxford: Wiley-Blackwell.
8. Rhim, J. W. (2010). Effect of moisture content on tensile properties of paer-based food packaging materials. *Food Science adn Biotechnolody, 19,* 243–247.
9. Navaranjan, N., & Johnson, B. (2006). *Modelling and experimental study of creep behaviour of corrugated paperboard*. Melbourne, Australia: Publisher.
10. Pathare, P. B., & Opara, U. L. (2016). Changes in moisture content an compression strength during storage of ventilated corrugatedpackaging used for handling apples. *Packaging Research, 1,* 1–6.
11. Frank, B. (2014). Corrugated box compression-a literature survey. *Packaging Technology and Science,* 105–128.
12. Katsuoki, K. (1989). Estimation of the compression strength of corrugated fibreboard boxes and its application to box design using a personal computer. *Packaging Technology and Science, 2,* 29–39.
13. Kellicutt, K. Q., & Landt, E. F. (1951). Safe stacking life of corrugated boxes. *Fibre Containers, 36,* 28–38.
14. Maltenfort, G.G. (1956). Compression strength of corrugated container. *Fibre Containers, 41*.

15. McKee, R. C., Gander, J. W., & Wachuta, J. R. (1961). Edgewise compressive strength of corrugated board. *Paperboard Packaging, 46,* 70–76.
16. Schrampfer, K. E., Whitsitt W. J., & Baum G. A. (1987). *Combined board edge crush (ECT) technology*. Appleton: Institute of Paper Chemistry.
17. Urbanik, T. J., & Frank, B. (2006). Box compression analysis of world-wide data spanning 46 years. *Wood and Fiber Science, 38,* 399–416.
18. Whitsitt, W. J., Gander, J. W., & McKee, R. C. (1968). *Effect of box dimensions and combined board creep life on box creep life*. Appleton: Institute of Paper Chemistry.
19. Sohrabpour, V., & Hellstrom, D. (2011). *Models and Software for Corrugated Board and Box Design*. Publisher.
20. Biancolini, M. E., & Brutti, C. (2003). Numerical and experimental investigation of the strength of corrugated board packages. *Packaging Technology and Science, 16,* 47–60.
21. Fadiji, T., Coetzee, C., & Opara, U. L. (2016). Compression strength of ventilated corrugated paperboard packages: Numerical modelling, experimental validation and effects of vent geometric design. *Biosystems Engineering, 151,* 231–247.
22. Han, J., & Park, J. M. (2007). Finite element analysis of vent/hand hole designs for corrugated fibreboard boxes. *Packaging Technology and Science, 20,* 39–47.