A FINITE ELEMENT INVESTIGATION OF THE ROLE OF ADHESIVE IN THE BUCKLING FAILURE OF CORRUGATED FIBERBOARD

Adeeb A. Rahman

Assistant Professor
Department of Civil Engineering and Mechanics
University of Wisconsin–Milwaukee
Milwaukee, WI 53211

and

Said Abubakr

Professor and Chairman
McCracken Hall, Welborn Hall
Western Michigan University
Kalamazoo, MI 49008

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ABSTRACT

Considerable research has focused on the role of linerboard and medium components in the overall strength of fiberboard. However, limited research has been done on the role of the adhesive in the structural performance of corrugated fiberboard and the container box. This research study proposed to include the glue material in a finite element (FE) model that represents the actual geometry and material properties of corrugated fiberboard. The model is a detailed representation of the different components of the structure (adhesive, linerboard, medium) to perform buckling analysis of corrugated structures under compressive loads. The objective of this analysis was to quantify the influence of the adhesive on the structural performance of corrugated fiberboard. Adhesive parameters are identified in terms of material properties. The modulus of elasticity of the adhesive is taken relative to the modulus of a linerboard material. Three adhesive stiffness properties representing minimum, medium, and maximum moduli values are considered. The analysis also addresses the buckling failure of fiberboard when adhesion is ineffective along a glueline. Results show that increasing the adhesive modulus (20 times that of linerboard) tends to strengthen the fiberboard buckling carrying capacity up to 50%. Loss of adhesive along a fiberboard glueline also substantially decreases the buckling strength of the structure.

Keywords: Corrugated fiberboard, buckling, finite element, adhesive.

INTRODUCTION

The overall strength and performance of a corrugated container are dependent on many factors, such as the engineering mechanical properties of the components (liner, medium, and adhesive), the manufacturing quality control protocol, machine precision, and the human factor involved in the corrugation process. Ultimately, all these factors affect the strength and performance of the resulting fiberboard. Although numerous studies have focused on the role of the linerboard and the medium components in the overall strength of the fiberboard (Considine 1992a; Byrd 1984), few have attempted to study the role of the adhesive in the structural performance of a corrugated fiberboard and the container box (Byrd 1986; Leake and Wojcik 1988). It is difficult to isolate the effect of adhesive in a fiberboard. Each corrugating company uses different adhesives; therefore, adhesive type changes from one product to another. The mechanical properties of thin film adhesive specimens are not representative of the

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adhesion interface layer (between the liner and the medium) developed in the processing phase. The properties of adhesives change as a result of service loading and environmental conditions, such as moisture and temperature. Lastly, chemical and mechanical bonds developed in the fiberboard are dependent on factors that involve special human techniques and individual manufacturing recipes.

Numerous studies have evaluated the mechanical and structural response of the linerboard and the medium components of corrugated fiberboard (Considine et al. 1989, 1992 a and b; Gunderson et al. 1986; Hahn et al. 1992). These studies were component oriented rather than structure oriented, and the role of adhesive was not considered. Performance of the actual corrugated fiberboard with an accurate fluted profile and a detailed contact interface between linerboard and medium has not been addressed. Several studies have presented elaborate analytical models that approximated the corrugated geometry by homogenous rectangular flat plates assembled along the long edges in a triangular formation (Urbanik 1995; Urbanik et al. 1993; Johnson and Urbanik 1987, 1989). These studies were adequate in predicting failure mechanism of the assumed structure. Many assumptions were made so that the formulation was adequate. However, a need exists to expand these models in a manner so that the actual geometry of the corrugated fiberboard with its detailed interface glue surfaces and fluted medium is represented. Previous research on gluelines and their structural role has not been done because computer models that require high performance computational capacity were not as available as they are today. The availability of large capacity finite element (FE) programs now makes it possible to incorporate all the structural components (linerboard, medium, and adhesive) of the corrugated fiberboard.

Buckling, creep, and moisture analyses of linerboard and medium materials have been studied for some time (Johnson and Urbanik 1987, 1989). However, the emphasis of these studies has been primarily on experimental investigations, with little emphasis on analytical studies. The role of adhesives as related to the structural performance of the corrugated fiberboard in a FE model has not been studied. The difficulty in isolating the role of adhesives experimentally has discouraged researchers from vigorously pursuing this problem.

In Byrd's (1986) study on the influence of adhesive on edge compression creep in a cyclic relative humidity environment, he pointed out the difficulty in trying to isolate the adhesive contribution to the corrugated structure in a short-column creep test. This study showed that water-resistant adhesive creeps nearly the same amount when compared with paperboard, and water-sensitive adhesive creeps 3.3 times faster in a cyclic relative humidity environment. Byrd's (1984) study reported that the corrugated fiberboard creeps 2 to 5 times faster than the creep measured for the components (medium and linerboard). These results show the importance of including the influence of adhesive as an active contributor to the overall response of the corrugated structure.

Inoue (1989) argued that the adhesive tends to reinforce the weak surface layer of the medium, thus influencing the failure of the corrugating board to occur in the linerboard. In a study by Urbanik et al. (1993), which was designed to evaluate the combined board performance under cyclic humidity conditions, they suggest caution when evaluating the performance of the adhesive. Urbanik et al. concluded that the adhesive interacts with either the linerboard or the corrugating medium to yield performance. When Urbanik (1996) compared the performance of regular adhesive with wet strength adhesive, the results were inconclusive as to which adhesive performed better. In his study, the adhesive was found to interact on some occasions with the linerboard and on others with the medium material. Therefore, Urbanik recommended additional testing to determine how the adhesive contributes to the local creep stability of corrugated boxes.

Leake and Wojcik (1988) argued that little is known about the contribution of a specific adhesive type on the actual stacking life of the container. They suggested that boxes made with a specialty high amylase starch-based adhesive greatly improved performance when compared with boxes made with a standard corn starch adhesive.

FE BUCKLING ANALYSIS

The FE buckling analysis presented here is an eigenvalue linear analysis, which is based on the stress stiffening theory. Buckling occurs when membrane strain energy is exchanged for bending strain energy without any input of external work. When the bending stiffness of a plate structure is reduced to zero by the action of compressive membrane forces, buckling occurs. When the membrane forces are applied in a tensile action rather than compressive, bending stiffness is effectively increased. This is called stress stiffening (Cook et al. 1989).

The buckling problem can be formulated as an eigenvalue problem:

$$([K] + \lambda_i[S])\,\{\psi_i\} = \{0\} \qquad (1)$$

where

$[K]$ = stiffness matrix of structure,
$[S]$ = stress stiffness matrix,
λ_i = ith eigenvalue (buckling factor multiplier), and
$\{\psi_i\}$ = ith eigenvector of displacements.

The FE buckling analysis uses the subspace iteration method to extract the eigenvalues and the eigenvectors in the buckling analysis. Usually the first (lowest) eigenvalue and the corresponding eigenvector are the most relevant (Bathe 1982). The solution of the previous equation yields the lowest eigenvalue buckling multiplier that effectively exchanges all the membrane strain energy of the plate structure into an equal amount of bending strain energy. The critical buckling stress would produce an equilibrium buckled configuration of the plate structure. For this configuration, an additional infinitesimal displacement can be induced without change in the applied critical stress. Beyond this displacement instability, failure occurs.

THE FE MODEL

The FE model was developed to represent a typical C-fluted geometry of a corrugated panel. The analysis has been conducted using the commercial finite element program ANSYS (version 5.7 and version 6.0). The corrugated fiberboard modeled in this analysis consisted of a liner, medium, and adhesive layer. The liner and the medium were modeled as 8-node shell elements that allow for curved medium. The glueline juncture was modeled by a three-layer composite 8-node shell element. This allowed the designation of three distinct layers of materials. The liner paperboard material was on the outer layer, the adhesive was the middle, and the medium as the inner layer. The liner and medium were assigned orthotropic material properties based on experimental data (shown in Table 1), Gilchrist (1995). The adhesive properties were taken to be relative to the liner mechanical properties. This detailed level of modeling allowed for an adequate level of investigation of the buckling response of the different components. A total of 2,744 elements were used with active degrees of freedom in excess of 25,000 degrees. Figure 1 is a detailed representation of the FE geometry and loading condition for the eigenvalue buckling analysis. The liner and medium materials are considered orthotropic; the major orthogonality directions are the cross machine direction (CD) of paper, machine direction (MD) of paper, and the out-of-plane z-direction of paper. The elastic modulus (E) in the later z-direction is taken to be 1/10 that of the CD direction. Table 1 shows the choice of orthotropic material properties used for the fiberboard components. The corrugated panel was loaded by an edge-wise compressive

TABLE 1. *Orthotropic material properties of fiberboard components.*

Medium			Liner		
E_{MD}	=	5.9 GPa	E_{MD}	=	7.23 GPa
E_{CD}	=	1.688 GPa	E_{CD}	=	2.68 GPa
Ez	=	$E_{CD}/10$	Ez	=	$E_{CD}/10$
$V_{MD,CD}$	=	0.41	$V_{MD,CD}$	=	0.44
$G_{MD,CD}$	=	1.29 GPa	$G_{MD,CD}$	=	1.73 GPa

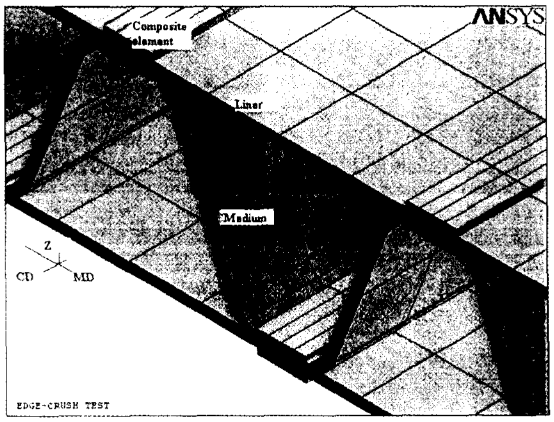

FIG. 1. 3D Finite element model of corrugated fiberboard showing: liner, medium, and gluelines. Front edge is pressure loaded, panel is symmetric about back edge (isometric view).

load along the CD of the liner. All four edges of the panel were simply supported. The rational for choosing simply supported edges is that, for a sealed container box in service, the bulging of the side panels is restrained at all the edges such that translation is prevented and rotation is allowed. This is a reasonable assumption that corresponds to simple supports at panel edges in a container box. The buckling results are sensitive to boundary condition assumptions as expected by plate buckling theory.

The eigenvalue buckling analysis was validated with the results obtained from experiments performed by Kuskowski (1995a), with theoretical analysis reported by Urbanik (1981), and by the homogenous orthotropic plate buckling theory, (Rahman 1997). The theoretical results were obtained by performing a FE buckling analysis of a homogenous orthotropic plate structure loaded along the edge with a compressive load. The plate was simply supported at four edges and free to deflect in the direction of the applied load. This the most representative case of the boundary conditions of the side panel of a container box. The liner orthotropic material properties were used.

The analysis was performed to evaluate the effect of changing the adhesive properties as a factor of the paper properties. This was done because starch adhesive mechanical properties are not well documented, and they vary from one corrugating plant to another. In addition, the pure adhesive thin film properties do not necessarily represent the actual properties of the adhesive that has penetrated the paper. Maximum and minimum values of adhesive properties in the model allowed for a wide range of possible glueline stiffness and provided the engineering design parameters necessary to draw accurate conclusions on the role of adhesive in the fiberboard design and strength evaluation. Variations of the adhesive component of the fiberboard design are presented in Table 2.

The variations in fiberboard design (Table 2) show different parametric board designs related to adhesive effectiveness. The adhesive thickness was kept constant throughout the analysis. The thickness of the medium and the liner was taken to be 0.254 mm, and thickness of the adhesive was taken to be 0.0635mm, one fourth that of paper. This is based on averaged microscopic measurements of a corrugated fiberboard made of 42# Virgin Liner and 26# Green Liquor medium paper type. The measurements were conducted at the Forest Products Laboratory in

TABLE 2. *Fiberboard design variations*[a].

Fiberboard	Fiberboard design	Adhesive properties
1	Adhesive properties are same as liner, perfect joint bond.	Reference board
2	Adhesive modulus is 10 times that of liner.	
3	Adhesive modulus is 20 times that of liner.	Maximum adhesive strength
4	One glueline is defective (no liner to medium bond at this location).	Liner around missing glueline determines critical failure stress

[a] Adhesive thickness is 0.0635 mm.

Madison, Wisconsin. Similar measurements are reported by Kuskowski (1995b).

RESULTS

Figure 2 shows the effect of adhesive properties on the buckling stress factor of a corrugated fiberboard. Four curves are shown, representing adhesive modulus values as a multiplier of the linerboard paper modulus (10x and 20x), a perfectly bonded fiberboard as a reference curve, and a buckling curve of a panel for a defective glueline. The corrugating panels have a constant width of 50.8 mm, and the length varies from 0.1 to 3.3 aspect ratio. The aspect ratio is defined as the ratio of length/width of the corrugated panel. The initial edge load per unit width of 1 KN/m is applied to the panels. Figure 2 shows the stress multiplier value that will cause the panel to become unstable for a range of aspect ratios. Figures 3 to 10 show a series of buckled panels for the corresponding curves. Selected values of aspect ratios for each curve are shown and give an example of the nature of the buckling failure resulting from an eigenvalue buckling analysis. An aspect ratio equal to 1 represents the dimension of the edge crush specimen. As the aspect ratio increases to a value equal to 3, the dimension represents a section of the side panel of a corrugated box.

DISCUSSION

The results obtained by the finite element model reported in this paper must be validated with reported experimental or theoretical results as available. The best examples of such available results were reported in an experimental report by Kuskowski (1995a), and in a theoretical report by Urbanik (1981). Both results are for the

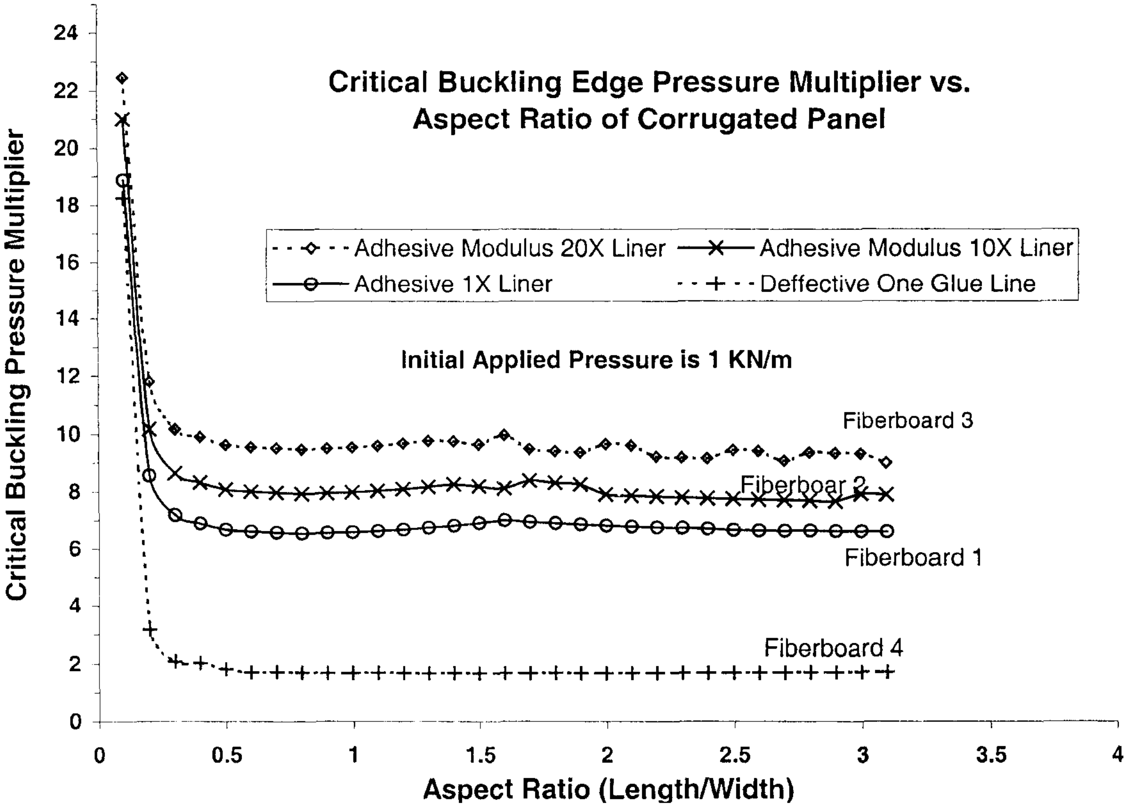

FIG. 2. Edge pressure multiplier vs. panel aspect ratio. Initial applied pressure is 1 KN/m of panel's width.

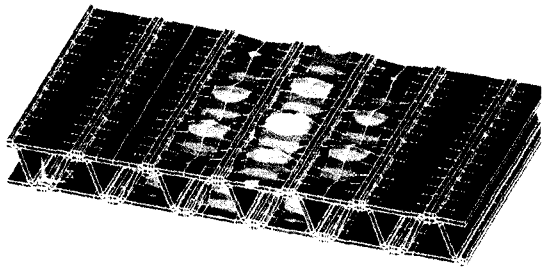

FIG. 3. Fiberboard with aspect ratio of 1.1 for a panel with glue modulus same as liner's (1X liner). Front edge is pressure loaded, panel is symmetric about back edge (isometric view).

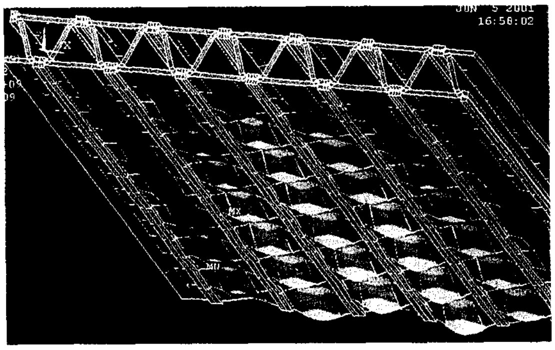

FIG. 4. Fiberboard with aspect ratio of 3.2. Glue modulus same as liner's. Front edge is pressure loaded, panel is symmetric about back edge (isometric view).

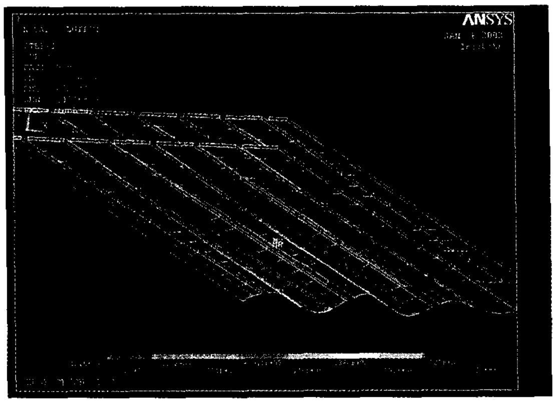

FIG. 5. Liner with aspect ratio of 3.3. Glue modulus is 10 times liner's. (10X liner). Front edge is pressure loaded, panel is symmetric about back edge (isometric view).

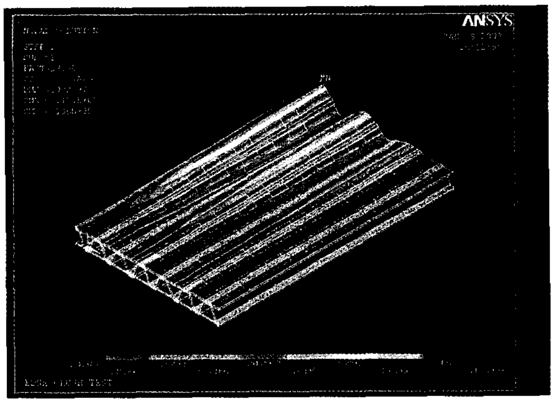

FIG. 6. Fiberboard with aspect ratio of 3.3. Glue modulus 10 times as liner's (10X liner). Front edge is pressure loaded, panel is symmetric about back edge (isometric view).

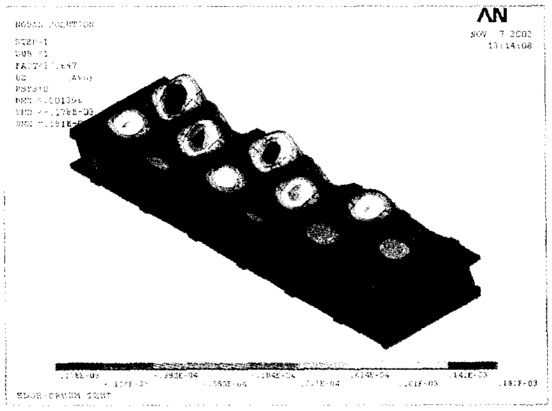

FIG. 7. Fiberboard with aspect ratio of 0.6. Glue modulus 20 times as liner's (X20 liner). Front edge is pressure loaded, panel is symmetric about back edge (isometric view).

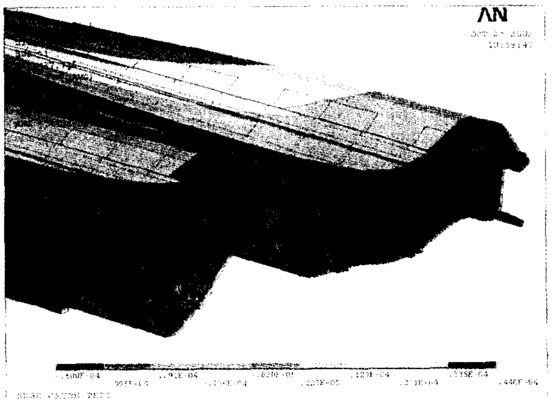

FIG. 8. Fiberboard (mid-panel section) with aspect ratio of 3.3. Glue modulus 20 times as liner's (X20 liner). Panel's cross-section at centerline (isometric view).

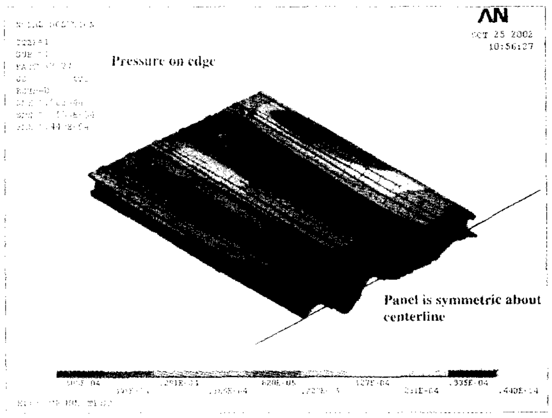

FIG. 9. Fiberboard with aspect ratio of 3.3. Glue modulus 20 times as liner's (X20 liner) (isometric view).

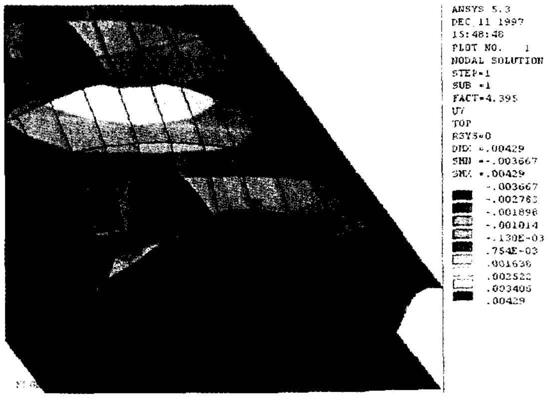

FIG. 10. Liner separation for fiberboard in the vicinity of defective glueline (isometric view).

Edge Compressive Test (ECT) of corrugated specimens. The finite element results reported here are for a slenderness ratio ranging from 0.1 to 3.3. The ECT is done for a specimen with an aspect ratio of 1.0. For this aspect ratio, the finite element bucking load multiplier is 7.38 for an initial applied edge load of 1 KN/m resulting in a buckling of 7.38 KN/m per unit width of the panel. In the experimental report by Kuskowski (1995), for a panel ID Y089, the ECT result is 7.34 KN/m. This represents less than 1% difference when compared to the finite element result. The analytical calculation for a similar panel reported by Urbanik (1981) gives an average ECT of 47.4 lb/in or 8.3 KN/m with an average standard deviation of 0.7 KN/m. This result is about 11% higher than the finite element results.

Given the differences in the finite element formulation, the experimental set-up, and the analytical assumptions, the variation in the results is insignificant. Comparison provides evidence of the accuracy of the finite element analysis reported in this research. Results of the eigenvalue buckling analysis are similar in pattern to the results reported by Bulson (1969) and Marsh and Smith (1945). However, the FE analysis presented here is more realistic because it analyzes the actual fluted corrugated geometry compared with an equivalent orthotropic plate presented by other analytical solutions. The mode shape of the buckling curve is essentially the same for all fiberboards, except for when the adhesive is defective along a glueline. In this case, the instability failure is associated with the liner plate surrounding the missing glue. The buckled shape of the liner causes the fiberboard to be unsuited structure as a result of excessive deformation, even though the fiberboard can support the applied load. In the structural analysis failure theory, this type of failure is known as excessive deformation failure.

For the reason mentioned, the adhesive engineering properties are taken relative to the liner paper properties. In the case where the stiffness of the adhesive was about 10 to 20 times that of the linerboard modulus, the increase in the panel buckling strength was 23.8% to 50%, respectively, relative to the standard fiberboard number 1. The analyses were also conducted for the case when the strength of the adhesive was 0.1 that for the liner, the reduction of the buckling load was 2.4% relative to the standard fiberboard. This suggests that an increase in the adhesive stiffness above that of the linerboard produces a stronger fiberboard. However, the reduction in adhesive stiffness below that of the linerboard, provided that the bond between liner and medium is intact, will not have a significant effect. As the stiffness of the adhesive increases, the joints where the medium and the liner meet are stiffer, resulting in a strengthening effect to the fiberboard. One conclusion can be drawn from this—as long as the glue provides a perfect bond to keep the fiberboard intact, loss of adhesive stiffness does not have an adverse effect in the short term; however the durability of such joints will be highly venerable resulting in short life of the fiberboard adhesion. On the other hand, an increase in adhesive stiffness has a strengthening effect and longer life of the joints. Fiberboard 4 shows a significant decrease of the buckling load for the case when a glueline was defective and bonding was lost at that location. The mode of instability failure in this case is associated with the buckling of the facing in the vicinity of the missing glueline as shown in Fig. 10. This does not necessarily mean that the overall fiberboard strength was reached; rather it shows that this load will buckle the liner, deeming the corrugated panel excessively deformed.

CONCLUSIONS

To function as a continuous structure, adhesive is used to provide the necessary bond needed for the liner and medium of a corrugated fiberboard. The corrugated panel strength and failure are affected by the properties of the adhesive. The first conclusion is that the adhesive should provide a continuous bond between components to ensure the structural integrity of the fiberboard. An increase in the modulus of elasticity of the adhesive increases the buckling strength of the fiberboard up to 50% when adhesive modulus is 20 times greater than liner's modulus. A decrease in adhesive properties relative to the linerboard stiffness (0.1 of liners modulus) does not dramatically change the fiberboard strength, provided a perfect bond is still present between components. However a weak bond is susceptible to durability failure resulting in a short bond life. This behavior can be explained by the load-sharing principle. For a stiff adhesive, part of the applied load is carried directly by the gluelines, resulting in a greater load-carrying capacity of the fiberboard. For weak but perfectly bonded gluelines, the applied load is carried entirely by the other components—the linerboard and medium. For a case when one glueline is missing or a glueline has a defective adhesive, two modes of failures can be observed. One mode is evident in the excessive deformation observed in the linerboard surrounding the missing glueline. Failure in the linerboard takes place, marking a loss of 80% of fiberboard strength. One additional conclusion relates to the buckling mode, for a small aspect ration and low adhesive stuffiness, the mode of failure observed as shown in Fig. 3 and Fig. 4 is a local indentation of the liner or the medium much like an edge crush test failure, for a large aspect ratio and a high adhesive stiffness, a global buckling failure is observed in a form of bulging-out of the panel and wave formation similar to the side-panel of a container box bulging-out as seen in Fig. 8 and Fig. 9.

It is observed that the finite element eigenvalue buckling analysis is very sensitive to the mesh refinement in the FE model. As the aspect ratio of the panel increased with each set of the new analyses, careful consideration was taken to ensure that the mesh refinement ratio remained constant as the aspect ratio increases from one set of analyses to the next. This insured that the FE mesh refinement is not a variable affecting the overall results.

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