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

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ABSTRACT

This research study proposed to include the glue material in a finite element model that represents the actual geometry and material properties of a 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 adhesive stiffness and material properties. The modulus of elasticity of the adhesive is taken relative to the modulus of a linerboard material. Three adhesive strength 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 glue line. 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 glue line substantially decreases the buckling strength of the structure.

INTRODUCTION

The overall strength and performance of a corrugated container box is dependent on many factors, namely, the engineering mechanical properties of the components: (liner, medium, and adhesive), the manufacturing quality control protocol, machine precision. and the human factors 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 et al. 1992, 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, Leak and Wojcik 1988). It is difficult to isolate the role of adhesive in a fiberboard for the following reasons. Different corrugating companies may use different adhesives: therefore. adhesive-type changes from one product to another. The mechanical properties of thin film adhesive specimens are not representative of the 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, the chemical and mechanical bonds developed in the fiberboard are dependent on many factors that involve human special techniques and unique manufacturing recipes.

Numerous studies have evaluated the mechanical and structural response of the linerboard and the medium components of the corrugated fiberboard (Considine et al. 1989, 1992; Gunderson et al. 1986, Hahn et al. 1929). These studies have been component oriented instead of structure oriented. The role of adhesives in these studies 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 (Urbanik et al. 1993, Urbanik 1995, Johnson and Urbanik 1987, 1989) have presented elaborate analytical models that approximated the corrugated geometry by homogenous rectangular flat plates assembled together at the long edges in a triangular formation. These studies were adequate in predicting design and failure mechanism of the assumed structure. Many assumptions were made for the formulation to be adequate. However, a need exists to expand on these models in a manner where the actual geometry of the corrugated fiberboard with its detailed interface glue surfaces and fluted medium are represented. Research on the glue lines and their structural role have not been included because elaborate computer models that require high performance computational capacity were not as available as they are today. The availability of large capacity finite element 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 mainly on experimental investigations. with little emphasis on analytical studies. The role of adhesives as it relates to the structural performance of the corrugated fiberboard in a finite element 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 adhesive's influence of edge compression creep in a cyclic relative humidity environment, he points 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) argues 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, he suggests that caution must be taken in the evaluation of the performance of the adhesive. He 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 container's actual stacking life. They suggested that boxes made with a specialty high amylose starch-based combining adhesive exhibited 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).

TABLE I-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	= $E_{CD}/l0$
$V_{MD,CD}$	= 0.41	$V_{MD,CD}$	= 0.44
$G_{MD,CD}$	= 1.29 GPa	$G_{MD,CD}$	= 1.73 GPa

The buckling problem is formulated as an eigenvalue problem:

$$\left([K] + \lambda_i[S]\right)\{\psi_i\} = \{0\}$$

where

$[K]$ = stiffness matrix of structure.

$[S]$ = stress stiffness matrix,

l_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) eigenvector 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 point of displacement instability, failure occurs.

THE FE MODEL

The FE model was developed to represent an actual C-fluted geometry of a corrugated panel. The corrugated fiberboard modeled in this analysis consists of a liner, medium, and adhesive layer. The liner and the medium are modeled as 8-node shell elements that allow for curved medium. The glue lines juncture is modeled by a three-layer composite 8-node shell element. This allows the designation of three distinct layers of materials. The liner paperboard material is on the outer layer, the adhesive is the middle, and the medium is the inner layer. The liner and the medium are assigned orthotropic material properties based on experimental data (shown in Table 1). The adhesive properties are taken to be relative to the liner mechanical properties. This detailed level of modeling allows for an adequate level of investigation of the buckling response of the different components. A total of up to 2744 elements are used with active degrees of freedom in excess of 25000 degrees. Figure 1 is a detailed representation of the FE geometry and loading condition for the eigenvalue buckling analysis. The liner and the 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 properties in the later z-direction are taken to be 1/10 that of the CD direction. Table 1

TABLE 2–FIBERBOARD DESIGN VARIATIONS[a]

Fiber-board	Fiberboard design	Adhesive properties
1	Adhesive properties 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	Adhesive modulus is 0.1 rimes that of liner	Minimum adhesive strength
5	One glue line is defective (no liner to medium bond at this location)	Liner around missing glue line determines critical failure stress
6	Liner material is removed around a glue line	Effective remaining board determines critical buckling stress

[a] Adhesive thickness is 0.0635 mm

shows the choice of orthotropic material properties used for the fiberboard components (Gilchrist 1995).

The corrugated panel is loaded by an edgewise compressive load along the CD of the liner. All edges of the panel are simply supported.

The eigenvalue buckling analysis was validated with the theoretical results by performing a FE buckling analysis of a homogenous orthotropic plate structure loaded along the edge with a compressive load (Rahman 1997). The plate was simply supported at all edges. The liner orthotropic material properties were used.

The analysis is performed to evaluate the affect of changing the adhesive properties as a factor of the paper properties. This is done because starch adhesive mechanical properties are not well documented and they vary from one corrugating plant to another. Also. the pure adhesive thin film properties do not necessarily represent the actual properties of the adhesive impeded in the paper. The maximum and minimum values of adhesive properties in the model allow for a wide range of possible glue line stiffness and provide the engineering design parameters necessary to draw proper conclusions on the role of adhesive in the fiberboard design and strength evaluation. Variations of the fiberboard design are presented in Table 2.

Variations in fiberboard design. represented in Table 2, show different parametric board designs related to adhesive effectiveness. The adhesive thickness is 0.635 mm, which is kept constant throughout the analysis. The medium, liner, and adhesive thicknesses are given in Table 3.

RESULTS

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

TABLE 3–THICKNESS OF COMPONENTS FOR THE CORRUGATED PANELS

Thickness	mm
Medium (c)	0.254
Liner (f)	0.254
Adhesive	0.0635

DISCUSSION

The results of the eigenvalue buckling analysis are similar in pattern to the results reported by Bulson (1969) and Marsh and Smith (1945). However. the finite element 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. expect for the case when the adhesive is defective along a glue line. In this case, the instability failure is associated with the liner plate surrounding the missing glue. The buckled shape of the liner redeems the fiberboard as an unstable structure as a result of excessive deformation, even though the fiberboard can support the applied load. This is the type of failure known as excessive, deformation failure in the structural analysis failure theory

The adhesive engineering properties are taken relative to the liner paper properties for the reason just mentioned. In the case where the stiffness of the adhesive is about 10 to 20 times that of the linerboard modulus, the increase in the panel buckling strength is 23.8% to 50%, respectively. relative to the standard fiberboard number 1. As for fiberboard 1. where the strength of the adhesive is 0.1 that for the liner. the reduction of the buckling load is 2.4% relative to the standard fiberboard. This suggests that an increase in the adhesive strength produces a stronger fiberboard. However, the reduction in adhesive strength, provided that the bond between liner and medium is intact, will not have a significant effect. This can be explained by the load shearing mechanism. For a weak bonded joint. the applied load to the fiberboard will be transferred to the linerboard and the medium components; therefore. no significant loss of strength is observed. However, for the stiff glue line joints. some of the applied load is transferred to the glue joints, resulting in a strengthening effect to the overall 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 However, for the previous reason, increasing adhesive strength has a strengthening effect Fiberboard 5 shows a significant decrease of the buckling load for the case when a glue line is defective and bonding is 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 glue line (shown in Figures 9 and 10). This does not necessarily mean that the overall fiberboard strength is reached. rather it shows that this load will buckle the liner, deeming the corrugated panel excessively deformed.

Durability of the adhesive bond, no doubt, has an effect on the strength of the fiberboard. However, this study did not address the durability issue. It focused on the adhesive stiffness effect at the initial construction of the corrugated fiberboard strength.

CONCLUDING REMARKS

Adhesive is used to provide the necessarily bond needed for the liner and the medium of a corrugated fiberboard structure to function as a continuum structure. The corrugated panel strength and failure are dependent on the adhesive properties. 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 linerboard modulus. A decrease in adhesive properties relative to the linerboard stiffness (0.1 of linerboard modulus) does not change the fiberboard strength in a dramatic way, provided that a perfect bond is still present between components. This behavior can be explained by the load sharing principle. For a stiff adhesive, part of the applied load is carried by the glue lines, resulting in a higher load carrying capacity of the fiberboard. For weak, yet perfectly bonded glue lines, the applied load is carried entirely by the other components-the linerboard and the medium. For the case when one glue line is missing or a defective adhesive is at a glue line, two mode of failures can be observed. One mode is evident in the excessive deformation observed in the linerboard surrounding the missing glue line. Failure in the linerboard takes place, marking a loss of 80% of fiberboard strength. If excessive deformation in the liner is considered acceptable. then the overall loss of strength is only 8%. This assumes that even though the fiberboard deformation in the linerboard location is excessive, the fiberboard can still carry more load. However, from a design point of view, excessive buckling of linerboard is not acceptable.

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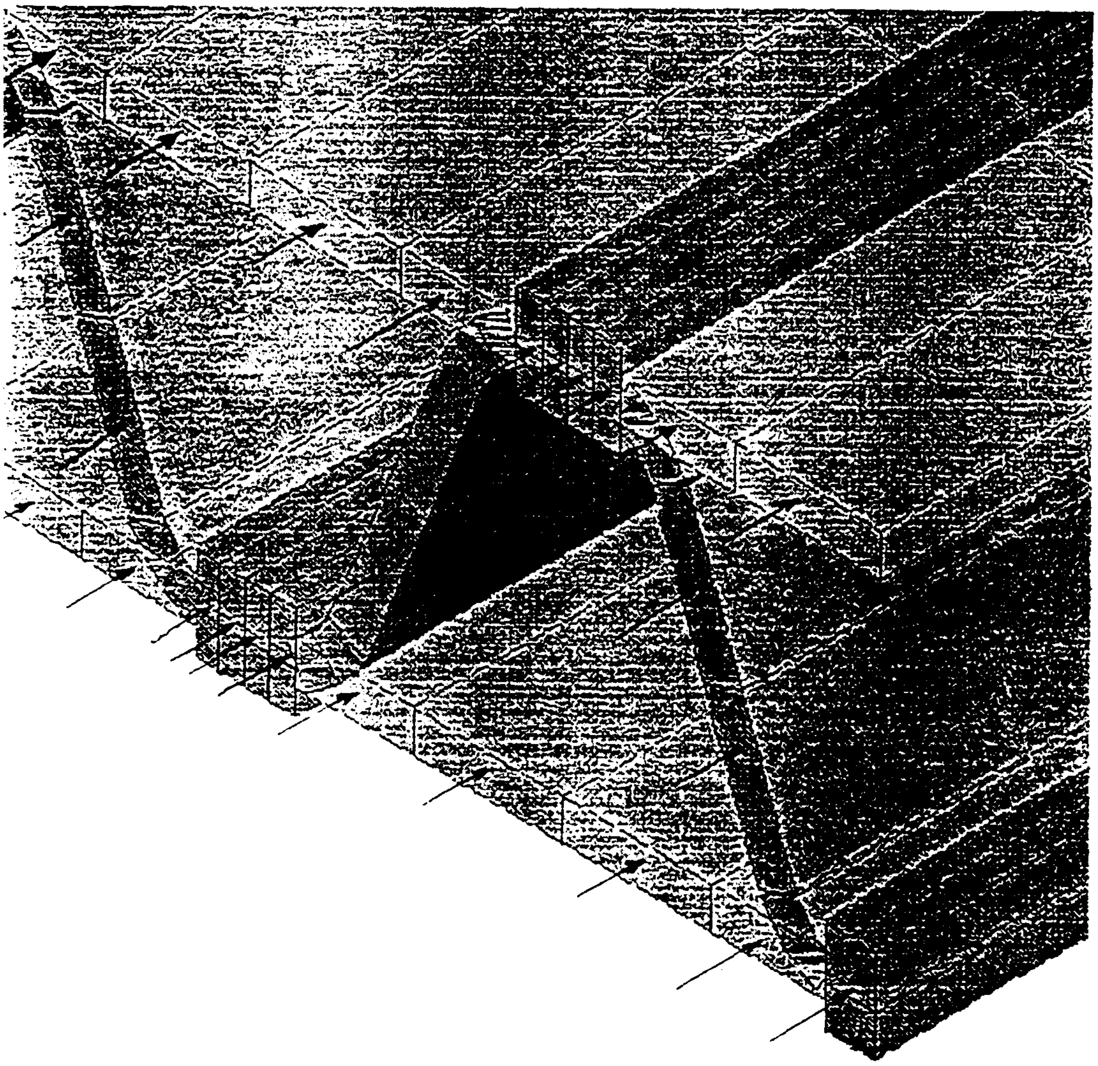


FIGURE 1. Finite element model of corrugated fiberboard

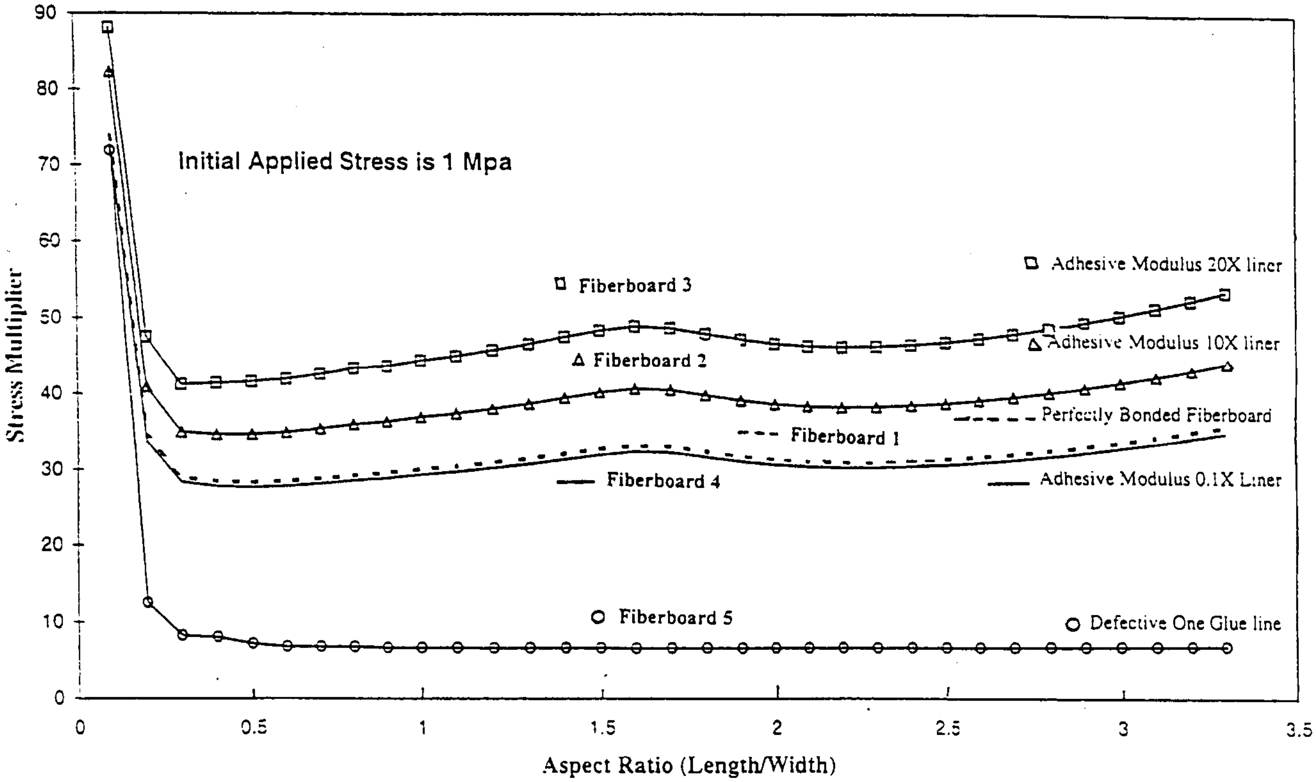


FIGURE 2. Buckling stress factor compared with aspect ratio of corrugated panels.

FIGURE 3. Buckled liner for fiberboard 1 (adhesive properties same as liner). Aspect ratio = 1.0; Buckled stress factor = 30.

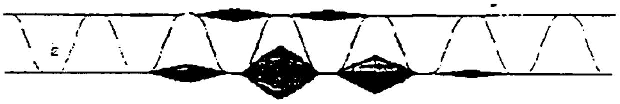


FIGURE 5. Buckled liner for fiberboard 2 (adhesive modulus is 10 times that of liner). Aspect ratio = 1.0; Buckled stress factor = 36.9.

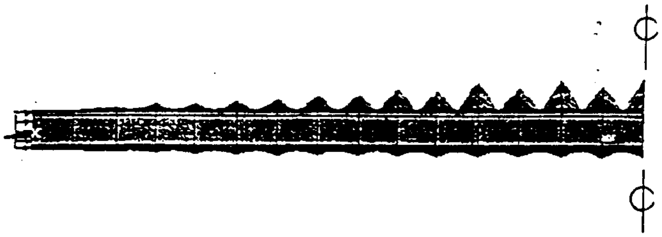


FIGURE 4. Buckled liner for fiberboard 1 (adhesive properties same as liner). Aspect ratio = 3.0; Buckled stress factor = 33.6.

FIGURE 6. Buckled liner for fiberboard 2 (adhesive modulus is 10 times that of liner). Aspect ratio = 3.0; Buckled stress factor = 41.6

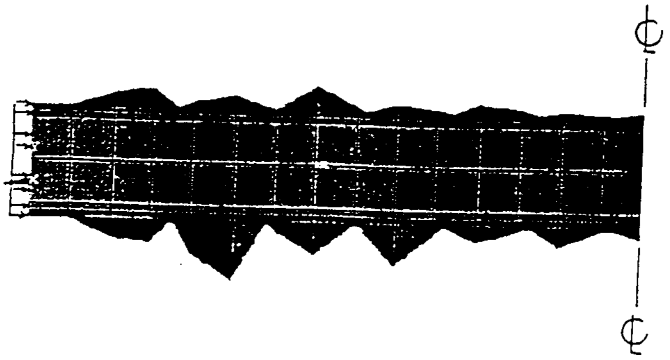


FIGURE 7. Buckled liner for fiberboard 3 (adhesive modulus is 20 times that of liner). Aspect ratio = 1.0; Buckled stress factor = 44.4

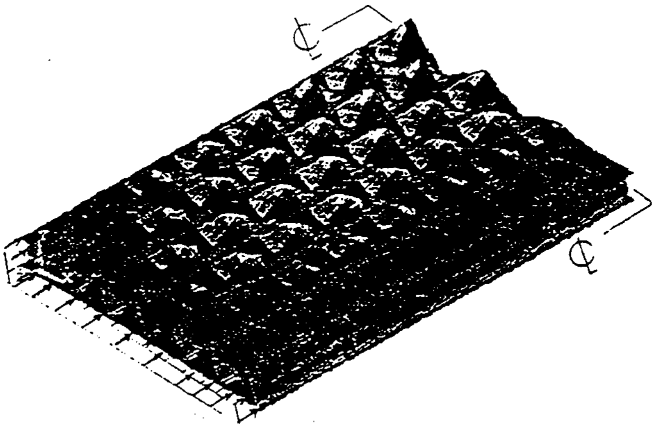
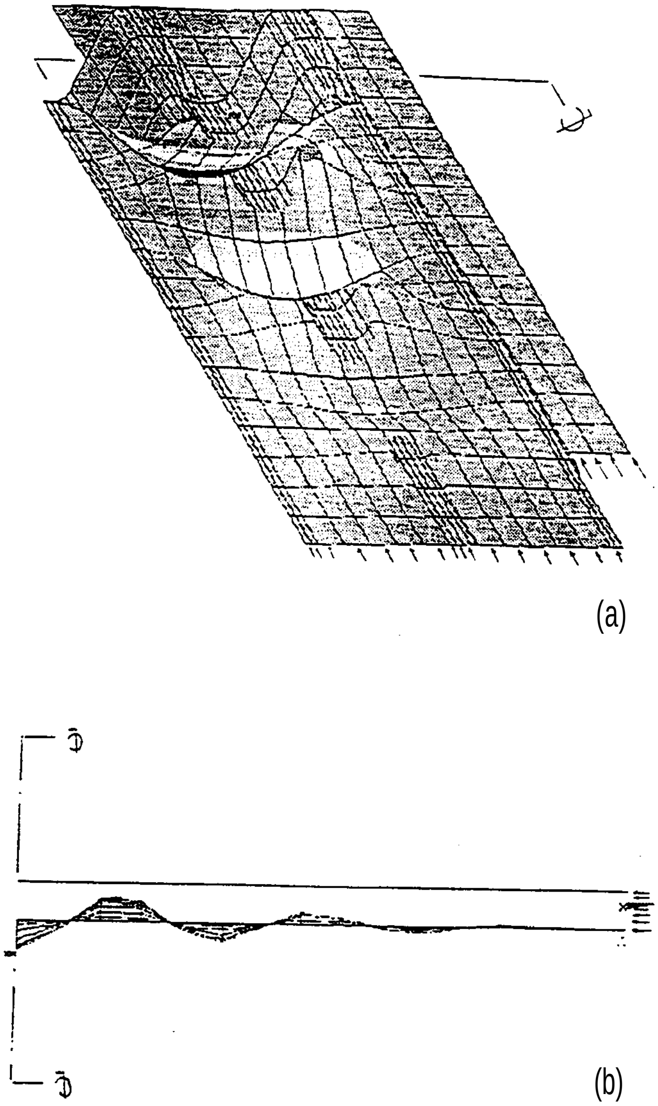


FIGURE 8. Buckled panel for fiberboard 3 (adhesive modulus is 20 times that of liner). Aspect ratio = 3.0; Buckled stress factor = 50.4.



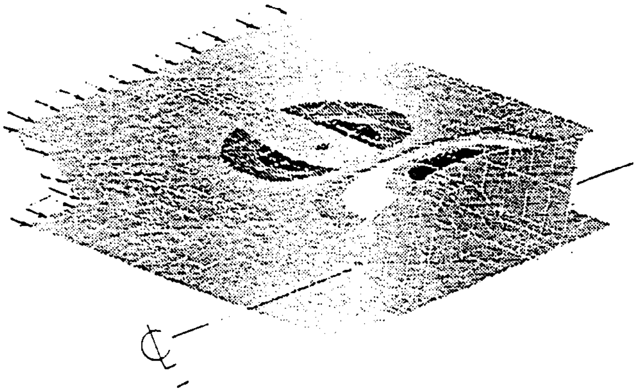


FIGURE 9. Buckled liner for fiberboard 5 (defective adhesive-one glue line is missing). Aspect ratio = 1.0; Buckled stress factor = 5.4

FIGURE 10. Buckled liner for fiberboard 5 (defective adhesive-one glue line is missing). Aspect ratio = 3.0. Buckled stress factor = 4.3: (a) front view, (b) side view.

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