Adhesive level effect on corrugated board strength – experiment and FE modeling

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Abstract

Corrugated board manufacture continually strives to reduce costs by minimizing component basis weight wherever possible. Lighter basis weight linerboard products are subjected to high densification are prone to out-of-plane interflute buckling when the corrugated board is subjected to vertical stress. An alternative means to increase board compressive strength is to limit this buckling mode through the application of more adhesive. Several different types of corrugating adhesives were prepared and their films measured for elastic properties. These adhesives were applied in a range of basis weights on the IPST double-backer simulator equipment. Resulting corrugated board samples were measured for changes in ECT and Bending Stiffness as a function of the applied adhesive level and type. Observed substantial increases in ECT indicate that some material cost savings can be obtained with an increased level of applied adhesive which allows a subsequent decrease in fiber amount. The findings are substantiated by a newly developed non-linear finite element (FE) model using shell-based elements including nonlinear geometric effects. Linerboard and medium layers are distinctly separately modeled along with their bonding areas (glue lines) with specified geometry. Material response of the linerboard and medium are simulated by the Hill anisotropic plasticity constitutive model. Test specimen damage locations occurring with progressive ECT loading are determined by the Tsai-Wu anisotropic failure criterion. Criterion meeting damage zones exceeding one flute spacing determine the predicted peak ECT failure load for a given set of ECT test conditions. The simulation predicted buckling loads, nonlinear load-deflection response, and other mechanical behavior modes confirm the observed effects of increased glue line volume on the ECT response.

Shown previously at the 2004 Progress in Paper Physics Seminar in Trondheim were the results of observations of linerboard interflute buckling when corrugated board is subjected to a vertical loading parallel the flute direction or CD of the board. In parallel with the reasoning of the development of the McKee equation for the ultimate failure load of buckling paneled boxes under vertical load, it was postulated that the compressive failure of corrugated board can also incorporate the panel buckling of linerboard panels simply held between the glue lines such that the critical buckling load P_{cr} of linerboard facings can be expressed as

$$P_{cr} = \frac{4\pi^2\sqrt{D_{11}D_{22}}}{Kb_f^{\;2}} \qquad (1)$$

$(D_{11}D_{22})^{1/2}$ represents the geometric mean (MD-CD) flexural rigidity of the plate approximated by the bending stiffness, b_f is the flute spacing, and K is a constant reflecting the restraint to rotation offered at the flute tips. In our experimental studies K was found to be equal to one indicating that the linerboard facing panels are simply held between the glue lines. The buckling occurs if the linerboard is sufficiently strong in compressive strength to exceed the buckling load thus leading to a predictive model for the compressive failure load (ECT) of corrugated board by:

$$ECT = 0.646 \left\{ 2\times (STFI_{liner})^{0.845} (P_{cr})^{0.155} + \alpha (STFI_{medium}) \right\} \; if \;\; STFI_{liner} \geq P_{cr}, \; liner \;\; buckling \;\; occurs$$

$$= 0.695 \left\{ 2 \times (STFI_{liner} + \alpha (STFI_{medium}) \right\} \; if \;\; P_{cr} \geq STFI_{liner}, \; Whitsitt \;\; formula \;\; holds$$

where $STFI_i$ is the short span compressive strength of either the liner or fluting medium, and α is the length weighting take-up factor equal to 1.42 for C-flute corrugation. The constants in the model were fitted for data using a variety of handsheet linerboards of various basis weights pressed to various densities. Similar relationships were found to hold for data sets consisting of commercially made boards and a variety of IPST made corrugated boards of various flute sizes and configurations using commercially supplied components.

Figure 1. Instantaneous snapshot of an AC multi-wall board undergoing an ECT test. The A-flute side (in the mirror view) has already failed while the C-flute side displays a buckling pattern.

Linerboard buckling limits the potential ECT as may be gleaned from typical values for 205 gsm linerboard and 125 gsm medium. An example of linerboard buckling occurring during an ECT test is shown in Figure 1. The linerboard STFI compressive strength is 4.6 kN/m, the medium compression strength is 2.4 kN/m and the geometric mean bending stiffness is measured as 6.9 mN-m for the samples used in our study. For typical C-flute spacing of 7.8 mm, the critical buckling load is 4.4 kN/m so that buckling can be expected and the ECT is predicted to be 7.5 kN/m. However, if buckling were not to occur, then the Whitsitt summation of length weighted compressive strengths predicts an ECT of 8.8 kN/m, an increase of 17%.

Simulation of ECT behavior was undertaken using a non-linear model and ABAQUS software. The stress-strain behavior of the components are characterized by a bi-linear elastic-plastic model based on laboratory measurements of the tensile stress strain and compressive failure behavior linerboard and medium components based on incremental anisotropic plasticity (Hill plasticity model) and new nonlinear elements (crease elements) to simulate buckling, post-buckling with progressive failure. The onset of plastic deformation is predicted using the anisotropic failure criterion of Hill[1] and recently applied by Lund University.[2] When stresses are relatively low, the response is initially linear. As loading progresses and stresses increase, the response becomes nonlinear elastic. As compressive loads are increased further, irreversible plastic deformations are initiated. The Hill anisotropic yield function can be used. This yield function in terms of the directional stresses σ_{ij} can be generally expressed as:

$$f(\sigma) = \left(F(\sigma_{22}-\sigma_{33})^2 + G(\sigma_{33}-\sigma_{11})^2 + H(\sigma_{11}-\sigma_{22})^2 + 2L\sigma_{23}^2 + 2M\sigma_{13}^2 + 2N\sigma_{12}^2\right)^{\frac{1}{2}}$$

where F, G, H, L, M, and N are material coefficients that control the plastic surface that bounds the elastic zone. A similar form for the Tsai-Wu anisotropic failure function with different material coefficients

$$F_1\sigma_{11} + F_2\sigma_{22} + F_{11}\sigma_{11}{}^2 + F_{22}\sigma_{22}{}^2 + F_{66}\sigma_{12}{}^2 + 2F_{12}\sigma_{11}\sigma_{22} = 1.0$$

is added to detect material failure. We use the Tsai-Wu criterion which accounts for the interaction of directional loads as the ultimate failure criterion. The model was validated by comparison of the simulated load where the zone satisfying the Tsai-Wu criterion exceeded one flute spacing across the corrugated board with the ECT peak loads. The comparison was made for A, B, C and E flute boards made and characterized at IPST facilities. Films of acrylic, starch and PVA were prepared and tensile tests were conducted to determine the apparent modulus from the stress-strain curves the slopes taken between 0.1 and 0.3% strain as customary for polymeric materials. For fully dried starch adhesive we use the value of 400 MPa and assuming homogeneity a Poisson's ratio of 0.3 in the FE simulations which show that with the inclusion of a glue layer as a third element, the predicted ECT value initially decreases which may be expected from the introduction of a polymeric layer of a modulus 10 times lower than that of the linerboard. The flute-linerboard interfaces are modeled as fused but hinged elements allowing the linerboard to buckle out of plane during vertical compression of the board. When adhesive is introduced into the model, the flute tips then have additional freedom lowering the ECT compared to the case without adhesive where the flute tips are fused to the linerboard.

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[1] Hill, R., Mathematical Theory of Plasticity, Oxford University Press, 1950.

[2] Beldie, L., Sandberg, G., and Sandberg, L., "Paperboard packages exposed to static loads – finite element modeling and experiments," Packaging Technology and Science, Vol. 14, pp.171-178, 2001.

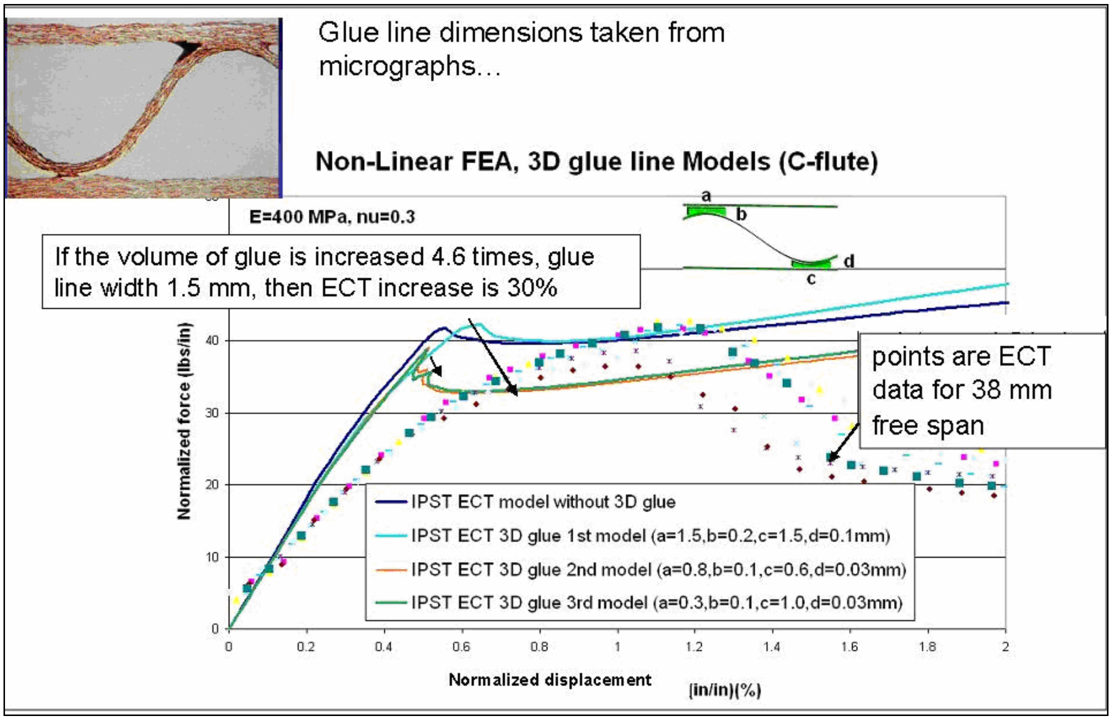

Figure 2. Summary of FEA ECT results (specimen vertical free span 38 mm) with differing amounts of starch adhesive. Adhesive levels are indicated by widths a and c and thicknesses b and d. Micrograph insert taken from Skuratowicz, R., *Corrugating International*, 2003.

However, increasing the width of the applied adhesive from 0.7 mm to 1.5mm suggests, as indicated in Figure 2, that a substantial increase in ECT will be obtained. Comparison with experimental data shows that the Tsai-Wu failure zones develop to a region exceeding one flute spacing which occurs at strains of 0.8% and coincides with the experimental observation of peak ECT load. Thus, once the adhesive level is increased to cover a substantial width, an increase in ECT may be expected attributable to the additional rigidity that the glue impart inhibiting out of plane buckling. Examining the FE simulated out-of-plane amplitude attained at a compressive strain of 0.55% shows that without any adhesive (perfect fused bonding) the buckling amplitude is 40 μm, with a small amount of adhesive present this becomes 310 microns from the additional freedom introduced at the flute-linerboard hinge. However, the out-of plane buckling then becomes 280 microns with an intermediate level of adhesive and finally decreases to 10 microns with the maximum amount of adhesive applied in the simulations. Adhesive contribution to strength cannot be through its penetration into the linerboard and its modulus and volume is too low. Indeed, the effective modulus of the combined board is modeled as:

$$E_{eff} = \sum_{i}^{i=3} \alpha_i E_i$$

where E_i is the modulus of either the linerboard, medium or adhesive and α_i is the respective volume fraction of corrugated board components as may be gleaned from cross sectional micrographs. Then the estimated increase from the presence of starch adhesive (modulus 400 MPa), linerboard (CD modulus 2.1 GPa) and medium (CD modulus 1.6 GPa) is only 3%. Therefore, the additional gains in compressive strength predicted in the FE model from the inclusion of adhesive appears to be due to an increase in structural rigidity or the elimination of linerboard buckling.

The analyses and results presented here are similar to those reported by Rahman and Abubakr[3] except there the adhesive was taken to have 10 and 20 times the modulus of the linerboard and found the resulting ECT load to increase from 24 to 50% of the initial value. When the modulus was reduced to 0.1 times that of the linerboard as in the current model, their finding is that buckling load is reduced by 2.4% relative to the standard board.

Thus we posit the inhibition of inter-flute liner buckling as the mechanism of an apparent increase in ECT with the addition of adhesive. In our FE study we find that the introduction of the adhesive as a third element substantially decreases the simulated buckling load from the case of a simulated perfect bond where kinematic constraints were directly attached to the liners and medium and no adhesive present. The simulation buckling loads results approach the perfect liner-medium bond case with an increasing glue volume.

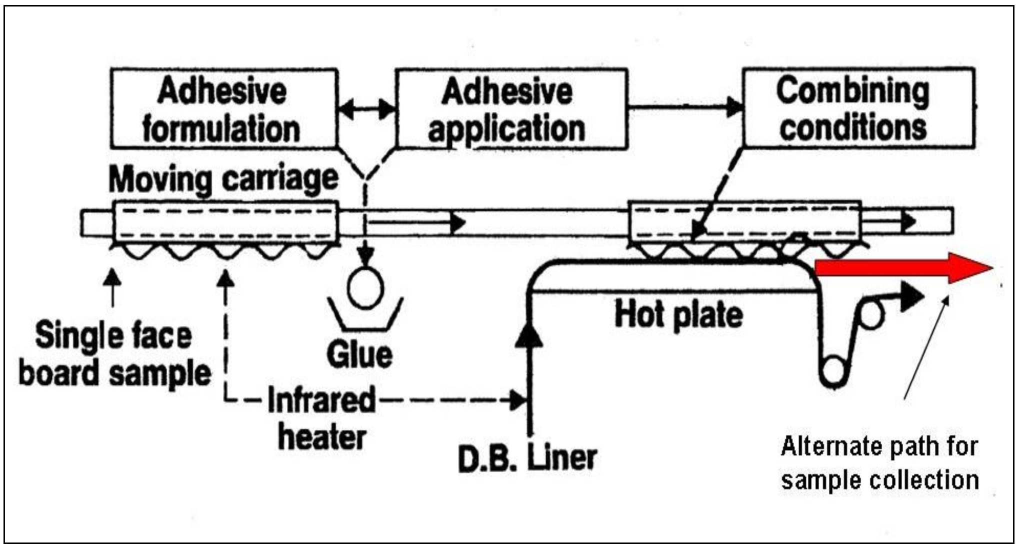

Figure 3. Schematic of the IPST double backer simulator used to apply varying glue types at various levels to single face samples.

An experimental plan was undertaken to verify the predictions from numercial and analystical analyses. A double backer simulator developed at IPST[4] was used to apply various adhesives to previously prepared single-face samples. The schematic of the double-backer simulator is shown in Figure 3. This device simulates a double backing operation through the inclusion of liner and medium preheating, adhesive application employing a doctored gravure roll applicator, and combining through a pressurized hot plate. A two by twelve inch single-face board adhered to a conveyed carriage moves over an infrared preheater and the glue roll where adhesive is applied at a set velocity. The carriage continues forward and the single-face sample with adhesive contacts the linerboard which is fed from a roll unwind stand. Then the carriage pauses for a pre-determined time over a pressure actuated hot plate to combine the single-face with the pre-heated double-back liner.

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[3] Rahman, A.A. and Abubakr, S., "A Finite element investigation of the role of adhesive in the buckling failure of corrugated fiberboard" Wood and Fiber Science, 36(2), 2004 p 260 -268.
[4] Marcille-Lorenze, M., Whitsitt, W.J. "Double backer technology", Tappi Journal, May 1990, p 137

Samples are then removed from the carriage. Metering of the glue level is obtained through gap doctoring of the rotating engraved gravure roll immersed in adhesive heated to 37.8 degrees C. The doctor gap was set at 0.1, 0.2 and 0.4 millimeters to obtain a wide range of applied adhesive level. Measuring the masses of produced board samples and comparing the results to the weight of components makes the corresponding applied adhesive level to be 14.6, 19.5 and 36.6 gsm respectively.

Selected adhesives were standard high shear starch formulation, PVA of 60% solids, sodium silicate of 40% solids, an aqueous acrylic dispersion of 38% solids, and a modified starch adhesive. The study included the effects of acrylic and modified starch adhesive adhering acrylic coated linerboard to wicking resistant medium as part of a study for wax-replacement alternatives.

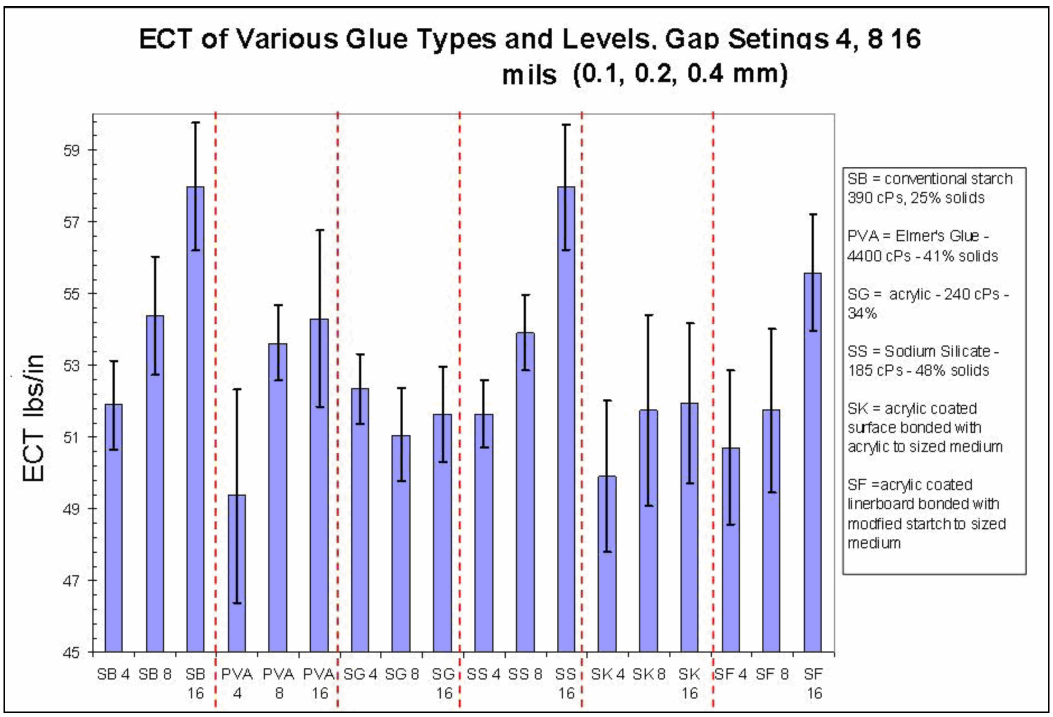

Figure 4. ECT of test boards made on the double backer simulator with varying adhesive type and adhesive levels. Numeric suffix denotes the adhesive applicator doctor gap setting in units of 0.001" (mils).

From Figure 4, it is apparent that ECT increases by as much as 12% with the increase in applied adhesive level from a 0.1 to a 0.4 millimeter applicator doctor gap level. Although the increase in ECT can result in less use of fiber to meet the same strength requirement, application of additional adhesive requires more drying capacity and can lead to dimensional stability problems such as board warp and washboarding which can impede standard box making operations and neagtivel impact container performance. The potential gains in board strength that can be realized with more adhesive may become more attractive in the near future with the application of adhesives at higher solids content than currently possible, thus requiring less water removal.