# Response of Corrugated Fiberboard to Moisture Flow: A 3-D Finite Element Transient Nonlinear Analysis

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### Abstract

Collapse of fiberboard packaging boxes, in the shipping industry, due to rise in humidity conditions is common and very costly. A 3D FE nonlinear model is developed to predict the moisture flow throughout a corrugated packaging fiberboard sandwich structure. The model predicts how the moisture diffusion will permeate through the layers of a fiberboard (medium and facings). The model predicts the deformation response, the loss of stiffness, and the creep response. The FE results are compared with an experimental set-up used at the Forest Product Laboratory in Madison, WI for a panel subjected to a swept-sine humidity function to study its response to varying humidity function. The panel modeled in this analysis consists of two facings made from liner material separated by a corrugated medium. The liner and medium will be assigned orthotropic stress-strain relations; bilinear stress-strain curves generated from experimental data under variable moisture contents namely 50% and 90% RH. The liner and medium will be modeled as 8-noded shell elements, which allow for curved medium geometry. The major orthogonal directions are the machine direction (MD), the cross machine direction (CD), and the out-of-plane z-direction. The layers are assumed perfectly bonded at juncture lines. The moisture flow is considered in one direction across the thickness of the fiberboard. The fiberboard will be subjected to transient moisture analysis coupled with an edgewise-compressive loading. The transient analysis is dependent on the following material constants: coefficient of moisture diffusivity, and coefficient of moisture expansion. The FE model will provide results showing moisture diffusion flow, creep deformation response in the fiberboard under the action of a static compressive loading and a periodic moisture actual experimental data.

*Keywords:*
*Corrugated fiberboard, finite element analysis FEA, moisture diffusion, liner, medium, coefficient of moisture conductivity, and coefficient of moisture expansion.*

## The Finite Element Model:

The FE model is 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 interface joints. The liner and the medium are modeled as 8-node shell elements, and the interface joints are modeled by 8-node layered shell elements. Figure 1 is a detailed representation of the FE geometry Rahman 1997. Rahman 2002 reports material properties.

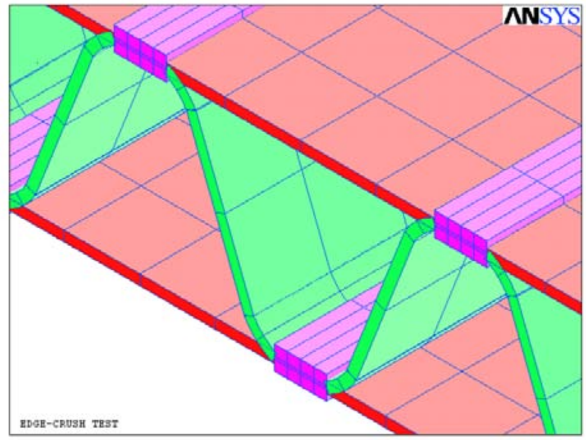


**Figure 1: FE geometry of the corrugated fiberboard**

A 2 in. by 2 in. corrugated panel is subjected to a steady state moisture flow due to rise in relative humidity from 50% to 90%. The finite element model analyzed is based on the experimental study conducted by Urbanik 1995 27(2). The experiment is conducted on a short column subjected to a single-frequency humidity function as shown in Figure 2.

## Theoretical

A derivation of two essential properties namely the coefficient of moisture conductivity $D_w$ and the coefficient of moisture expansion a for the liner and the medium materials are needed to make the finite element analysis possible. Rahman, 2002 shows the derivation of the constants. Table 1 summarizes the values used.

**Table 1: Diffusion Properties of Paper Sheet. Bandyopadhyay, 2001, Rahman, 2002**

| | |
|---|---|
| $D_w$ | 7e-6 $m^2/s$ |
| $\alpha$ (Liner) | 5e-5 /C |
| $\alpha$ (Medium) | 2.5e-5 /C |

Where:
$D_w$ is the coefficient of moisture diffusivity
$\alpha$ is the coefficient of moisture expansion

## Moisture Transient Analysis:

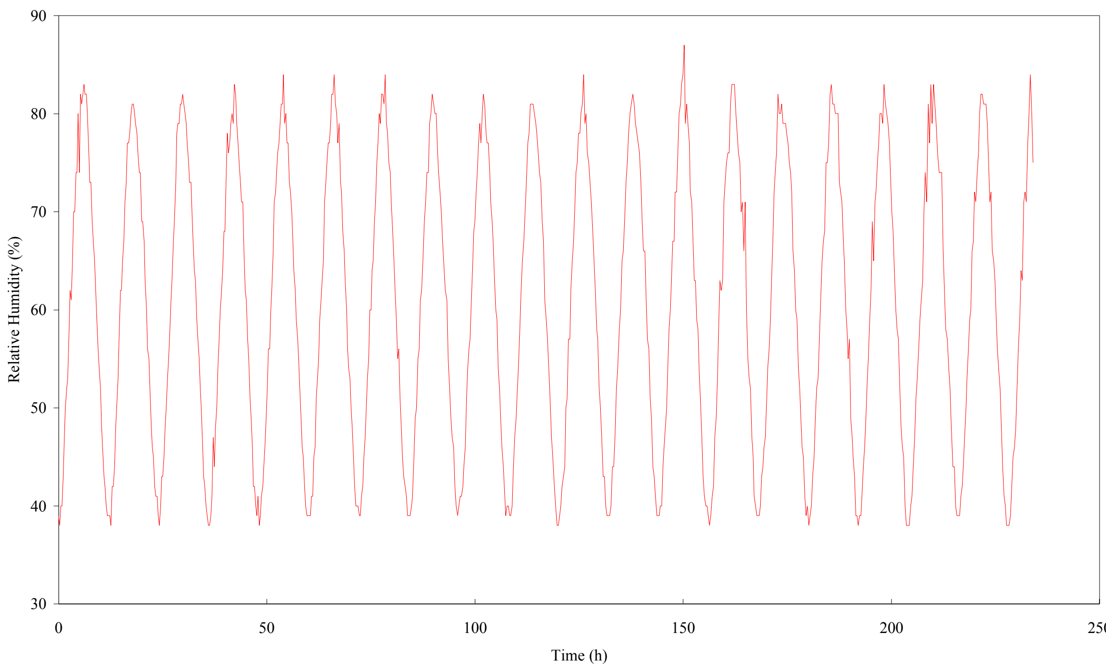


**Figure 2: Actual Experimental Relative Humidity Data Vs. Time used as Input (Urbanik 1995 27(2))**

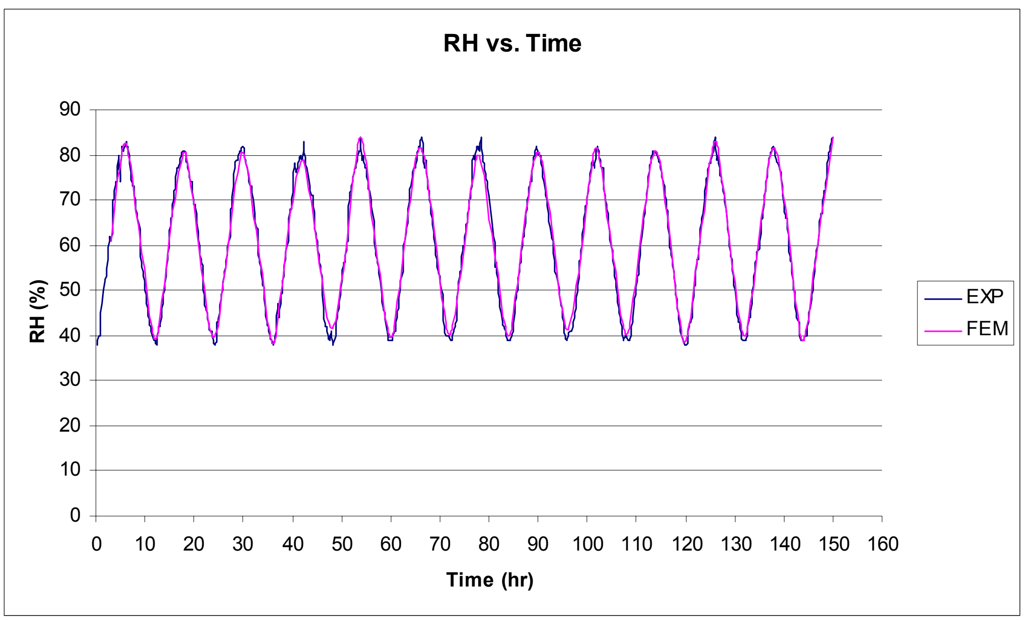


**Figure 3: RH Experimental Input and Corresponding FEA RH Output form Moisture Diffusion Analysis**

## Moisture stress analysis

The transient analysis is conducted first in order to calculate the relative humidity values throughout the fiberboard in all the layers as a function of time for time duration of 150 hrs. (6.25 days). The second stage of the analysis is to calculate the fiberboard deformation response (hygroexpansion) due to the change in relative humidity values. This analysis provides the deformation vs. time at different relative humidity values. The maximum deformation occurs at the highest level of RH (86%) and the minimum deformation is recovered at the lower RH value (38%). The deformation response of the structure is shown in Figure 4. The amplitude of deformation is about 0.1 mm. This is close to the amplitude value measured in the experiment. This hygroexpansion response is superimposed on the creep response to predict the overall response of the fiberboard.

## Nonlinear creep analysis

This FE research generates the creep model that describes the behavior of a typical paper material. Urbanik 2002 presented a creep model for paper; however, the equations generated do not

conform to creep equations' forms available in the finite element program in order to perform the creep analysis. The creep response is dependent on many factors including: material properties, the rate of loading, the time duration, and the relative humidity conditions.
The creep equation for the specimen described followed the following form

$$\varepsilon = \frac{C_1}{C_3 + 1}\sigma^{C_2} e^{-C_4} t^{C_3+1} \qquad (1)$$

Where:

$C_1$, $C_2$, $C_3$, $C_4$ are constants dependent on the material properties of the paper.
$\sigma$ is the compressive stress acting on the edge of the specimen, and
$t$ is the time in seconds.

The constants in the creep equations are dependent on the above factors. Changes in the relative humidity are reflected in the values of the constant $C_4$. Equation (2) gives the relationship between the constant $C_4$ as and the RH% within the interval of RH% considered (38%-86%)

### Table 2: Paper Creep Constants For Short Column (38% RH)

| | |
|---|---|
| $C_1$ | 5.11e-30 |
| $C_2$ | 4 |
| $C_3$ | -0.5882 |
| $C_4$ | -3.85 |

### Table 3: Paper Creep Constants For Short Column (86% RH)

| | |
|---|---|
| $C_1$ | 6.24e-30 |
| $C_2$ | 4 |
| $C_3$ | -0.5882 |
| $C_4$ | -3.65 |

Constant $C_4$ is affected by the relative humidity. The following equation is derived to relate the value of the constant $C_4$ to the relative humidity by the following equation:

$$C_4 = \left(\frac{RH - 38}{48}\right)(0.2) - 3.85 \qquad (2)$$

The short column finite element model considered is a 2 in. by 2 in. corrugated fiberboard while the experimental fiberboard is 2. in wide and 1.5 in. high (a standard Edge Crush test specimen). Therefore, defection adjustment for the height is used in order to produce the deflection creep response shown in Figure 4.

### Short Column Results:

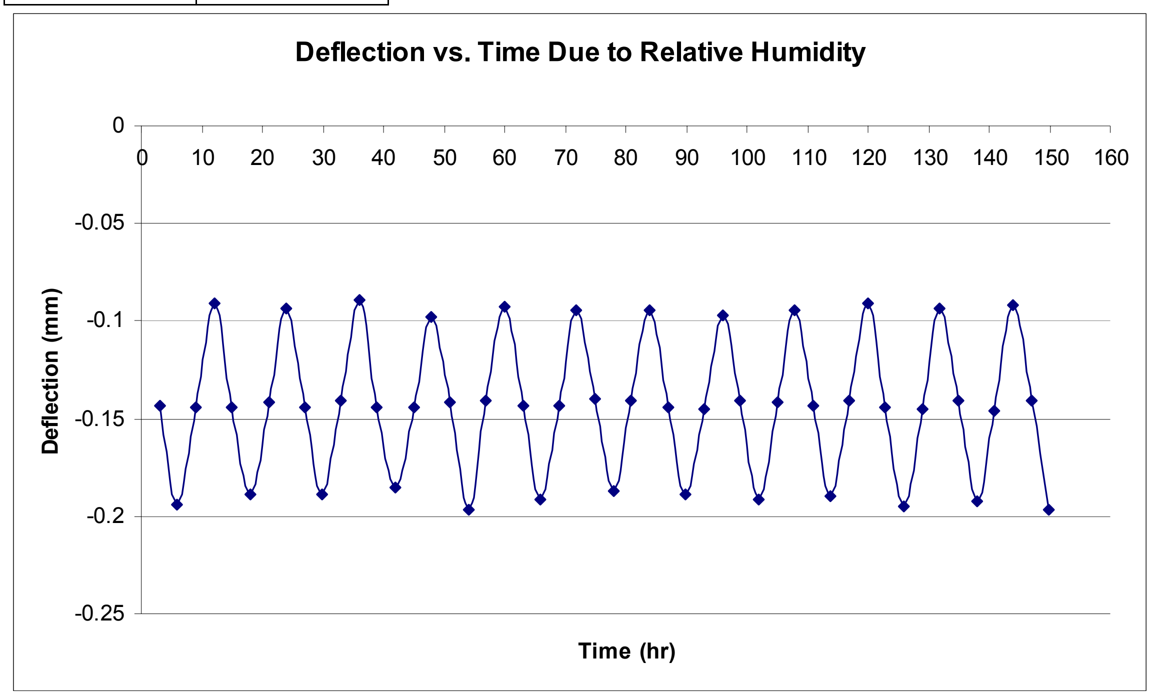


**Figure 4: FEA Hygroexpansion Response Due to RH Schedule**

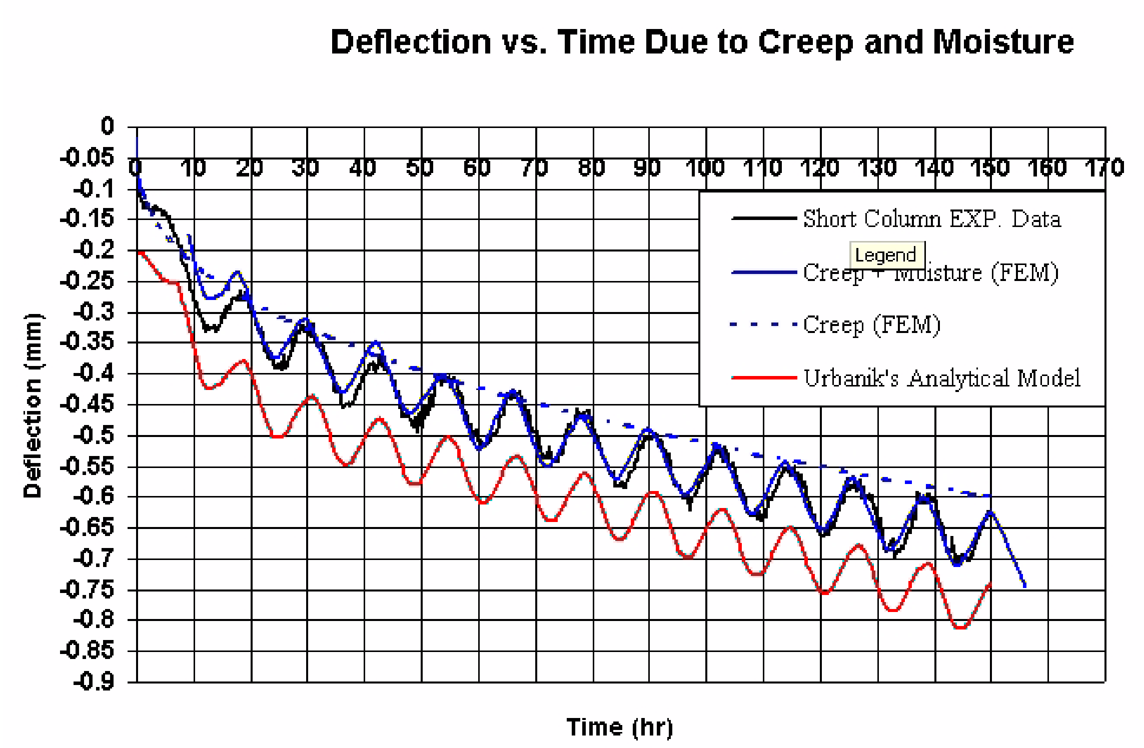


**Figure 5: Corrugated Short Column Deflection Due to Creep and Humidity Expansion**

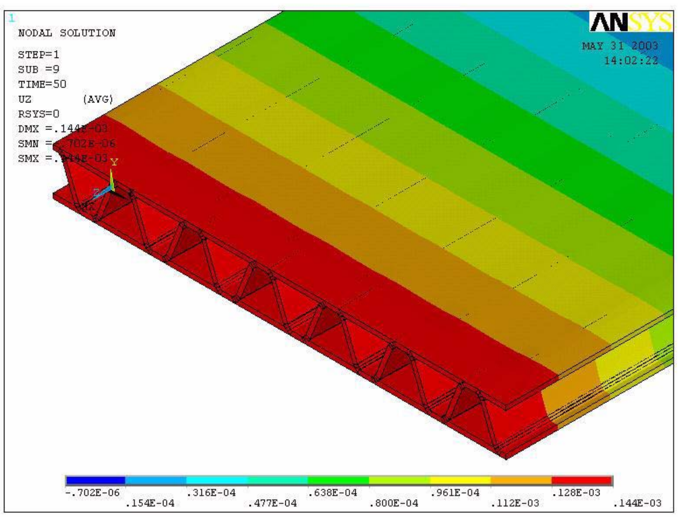


**Figure 6: Moisture Deformation due to 86% RH**

# Discussion and Conclusions

Figure 5 shows the total deformation response form the finite element analysis to the combined effect of humidity expansion and creep deformation. Very close correlation is observed between the FE results and the experimental results. An analytical model derived by Urbanik 1995 27(2) is also shown. The adjustments of the constants in equation (1) allows for calibrating the FFA for different paper type and moisture conditions. The transient moisture analysis, which is a dynamic nonlinear procedure is time consuming, and for a large model can present computational limitation. The nonlinear creep analysis however, is more rapid and can easily be performed for variety of constants modification for the creep equation.

The development of FE model to study the moisture expansion and the creep response by establishing a viable creep model for a paper material opens the possibility of considering actual weather data as an input to the model. This can predict the response of a corrugated container box in the field. This FEA is being expanded to predict a box-size-panel and its creep and hygroexpansion response to weather data.


### Acknowledgements

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