Using Computer Aided Engineering Processes in Packaging Design Development

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0.0 ABSTRACT
Utilizing Computer Aided Engineering has been a useful tool at Mabe during the product design development process, and now this tool has been found to be beneficial in improving the packaging design and optimization of the product-packaging system as well. The objectives of this project were to employ computer modelling to simulate the effect of the distribution environment events to the product-packaging system at early stages of the product design development and perform optimization to improve product protection.

1.0 INTRODUCTION
A critical aspect of being competitive in product design is to reduce development time while using a minimal amount of resources to deliver a competitive product that is desired in the market place. In product design it is critical to reduce development time with minimal effort and resources, in order to launch competitive products according to the market needs. Computer simulation is a strategy that helps to meet these needs. Traditionally, computer simulation was only applied to product development, and these tools were rarely utilized to study the effect of the distribution environment on the product. For packaging development, the main approach has been to physically test the product and packaging prototypes. With computer aided engineering we now have the capability of virtually testing different loading scenarios and/or alternate packaging designs before any physical testing is performed in the very early stages of the design program. This process will produce an optimized packaging design as well as a more robust product with adequate material costs.

2.0 OBJECTIVES AND SCOPE

2.1 Objectives
The primary objectives of this project were to use computer modelling to simulate the effect of distribution environment events to the product-packaging system at early stages of the product design development and perform optimization to improve product protection. An additional objective of this project was to apply technology transfer analytical simulation methods to accelerate current design efforts and future designs at Mabe.
2.2 Project Scope

The scope of this project was to first generate an accurate FEA (Finite Element Analysis) model representation of the product assembly (washer and dryer combination) and its packaging structure. The FEA model includes all necessary structural components of the product and packaging structure including EPS foams, laminate paper and corrugated board representations. Some of the product’s non-structural components needed to be idealized or excluded if determined structurally irrelevant as to minimize simulation model size. The computer models were then subjected to the same load cases as per physical testing procedure (ASTM D4169).

The following load cases were considered for the analyses:

- Straight Drop
- Front Side Impact
- Right Side Impact
- Back Side Impact
- Front Edge Drop
- Back Edge Drop
- Left Edge Drop
- Front Left Corner Drop
- Back Left Corner Drop

Other load cases such as clamp load and stacking load were not considered during dynamic load cases but were considered as static loads during packaging optimization. Initial material properties in the FEA of EPS foam, laminate paper and corrugated board were tuned to replicate the structural responses from physical tests.

Once a level of confidence from the FEA model was achieved, a set of baseline simulations were performed to determine the structural performance for each of the load cases stated above. The results from the baseline simulations were used as inputs to perform package topology optimization, which is done by converting dynamic loads to equivalent static loads. The topology optimization results provided the most optimum load paths for all the load cases combined. These results were then interpreted into an approximate production EPS package design. This design was then represented in a new FEA model for applying size and shape optimization to further improve and optimize design. Topology and size and shape optimization was also applied to the laminated paper corner posts to improve performance for all the combined loads including stacking load and clamp loads. Laminated paper thickness for the corner posts is considered for optimization but paper grade was not studied. Optimization of the EPS density and corrugated board grade was not part of this study but can be included in future studies. The product
structure was not altered or optimized in this study. Material properties were assumed to be only at room temperature but can be varied in subsequent studies.

3.0 PROJECT WORK PLAN

The work plan was divided into the following five phases, which are most common to Mabe and Altair’s simulation based optimization methods:

Phase 1:
CAD to FEA & Physical Test Prototype

A finite element model of the structure and packaging material was generated from CAD data of the washing machine and tumble dryer combination. The main product structure was mainly modeled with 2D shell elements with some of the structure being modeled with 3D solid elements, see Figures 1 and 2. All attachment welds and fasteners were modeled as rigid elements or 1D bar elements. Springs were modeled as 1D spring elements with pre-tension. Major masses such as the main electric motor was idealized and modeled as a mass element with inertia properties. EPS foams were modeled with 3D solid elements. Corrugate board and laminated paper were modeled with 2D shell elements, see Figure 3. The top cover steel strap was modeled as 2D shell elements with pre-tension springs and contact. The baseline model of the product structure was comprised of approximately 220,000 elements with approximately another 70,000 elements for the package structure. The simulation model was generated by a joint effort between Mabe and Altair ProductDesign.
Appropriate material properties were applied to each component in the model; steel and plastic material properties were used for the main product and foam, laminated paper and corrugate board material properties were used for the package. Generic material properties for EPS foam and paperboard were used to approximate for these materials since measured material properties were not available until next phase of the project. These assumptions allowed the model to be completed and subjected to the various dynamic impact load conditions. The results were studied to ensure the overall correct structural behavior and also to determine if the predicted impact ‘G’ loads were close to expected values at various locations on the product. EPS foam compressions were reviewed to ensure expected amount of compression was occurring for each of the load conditions. The model was generated with Altair® HyperMesh®, and dynamic impact, static analyses and optimization were performed using Altair HyperWorks suite of software tools.

**Physical Test Prototype:**

In order to establish a confidence level of the analysis results, two prototype tests were performed to correlate the analysis and the laboratory results. An internal testing procedure based on ASTM D4169 was applied during physical testing. The following tests were performed:

- Handling ASTM D6055 Method B
- Impact Test ASTM D-880
- Vehicle Vibration ASTM D-4728 3 hrs@ 0.52 g-rms"
- Clamp Handling D-6055 Method-C
- Handling ASTM D6055 Method B
- Impact Test ASTM D-880
- Fork Truck ASTM-D6179 Method C
- Tip test ASTM-D6179 Method F
- Drop Test ASTM D-5276

Results and observations from the physical test are shown in Table 1. Typical deformations and observations from the physical tests are shown in Images 1 through 4.
Sample Results

1.1 Deformation of washer cabinet where dryer sits
1.2 Deformation of front cabinet brace
1.3 Shipping rod out of position
1.4 Deformation of rear bottom brace
1.5 Deformation at bottom of cabinet sides
1.6 Deformation of back panel

2.1 Air duct out of position
2.2 Deformation of washer cabinet where dryer sits
2.3 Shipping rod out of position
2.4 Deformation of shipping rod
2.5 Deformation of side panel at rear bottom corner

Table 1: Results of Shipping Tests.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Results</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1.1 Deformation of washer cabinet where dryer sits</td>
</tr>
<tr>
<td></td>
<td>1.2 Deformation of front cabinet brace</td>
</tr>
<tr>
<td></td>
<td>1.3 Shipping rod out of position</td>
</tr>
<tr>
<td></td>
<td>1.4 Deformation of rear bottom brace</td>
</tr>
<tr>
<td></td>
<td>1.5 Deformation at bottom of cabinet sides</td>
</tr>
<tr>
<td></td>
<td>1.6 Deformation of back panel</td>
</tr>
<tr>
<td>2</td>
<td>2.1 Air duct out of position</td>
</tr>
<tr>
<td></td>
<td>2.2 Deformation of washer cabinet where dryer sits</td>
</tr>
<tr>
<td></td>
<td>2.3 Shipping rod out of position</td>
</tr>
<tr>
<td></td>
<td>2.4 Deformation of shipping rod</td>
</tr>
<tr>
<td></td>
<td>2.5 Deformation of side panel at rear bottom corner</td>
</tr>
</tbody>
</table>

Image 1: Physical Test Observation 1

Image 2: Physical Test Observation 2

Image 3: Physical Test Observation 3

Image 4: Physical Test Observation 4
Phase 2: Material Testing & Characterization

In order to obtain acceptable material properties of the EPS foam, especially a rate dependent stress strain curve, a simplified physical test was developed using EPS foam blocks. The main purpose of this test was to correlate the physical performance of the EPS foam to a computer model and adjust the properties to produce the exact performance seen in the physical test. Figure 4 shows a diagram of the simplified physical test set up.

Figure 4: Simplified Physical Test Setup.

High speed video capture was analyzed for a number of drop tests. A computer simulation model representing the actual physical test was then created and set up to replicate the drop tests. Figure 5 shows synchronized high speed video and simulation model during correlation.
Figure 5: High Speed Video v FEA Correlation

**EPS Foam**

The computer model was orientated to the same angles as that of the test product just prior to impact. Accelerations, EPS foam compressions and re-bound timings from the tests were compared to computer simulation results. Visco-elastic skeletal behavior of the material was tuned to improve the correlation of the computer model. A number of iterations were performed before arriving at desired material properties. Furthermore, compression testing at high and low speed was performed to obtain full stress verses strain curves for EPS foam.

**Corrugate Board**

To obtain accurate material properties for the corrugate board (box), flute (machine) direction and cross flute direction tensile tests were conducted on five tokens for each test. Engineering stress verses strain curves for both directions were obtained and converted to true stress verses strain curves for input into the simulation material model. Material properties in the third direction of the corrugate were derived by making an assumption on the modulus in the third direction and from performing strap tension correlation between test and analysis on the corrugate box top. Material properties in the third direction were adjusted in the simulation model until acceptable correlation of box corner crush was obtained. Although acceptable material properties of corrugate board were obtained, it must be noted that the corrugate board was not the main contributor to energy absorption during impact. It did however play an important role in retaining the assembly of the product, corner posts and EPS foam block in position during impact.
**Laminated paper properties for the corner posts:**

Material properties for the laminate paper corner posts were obtained by performing a top load test and correlating the results of the test to a computer model of the corner posts (see Figure 6). The two main material property parameters obtained were the modulus of elasticity and yield stress. This material was modeled with a bi-linear stress verses strain curve in the computer model.

**Figure 6: Corner Post Computer Simulation Results**

**Computer Simulation Material Models:**

The following material models were selected for dynamic impact simulation using Altair® RADIOSS™ explicit solver in the next phase:

- Steel: Material Law 36 (Elastic Plastic Piecewise Linear)
- Plastic: Material Law 1 (Linear Elastic)
- Foam: Material Law 33 (Visco-Elastic Plastic Closed Cell Foam)
- Corrugate Board: Material Law 19 (Linear Elastic Orthotropic)
- Laminated Paper: Material Law 36 (Elastic Plastic Piecewise Linear)
General computer simulation assumptions:

- Foam through thickness properties, or density assumed to be consistent
- Impact surface modeled as completely rigid
- Used post-vibration tested foam properties
- Load cases do not account for accumulated damage
- Strap tension is applied prior to impact loading
- Clamping was determined to be non-critical and was not included in the dynamic impact simulations
- Foam density remained unchanged throughout all dynamic impact simulations
- Main corrugated box and top cover parts remained unchanged throughout all dynamic impact simulations

Phase 3: Dynamic Impact Simulations

A total of nine baseline dynamic impact drop simulations were performed using the material properties of EPS foam, corrugate board and laminated paper obtained from Phase 2. A computer simulation results summary report for each of the nine load cases were generated using Altair® HyperView results post processor. An example of a typical report summary is shown in Figure 7. The result parameters of interest considered for each load case were peak product ‘g’ levels, top 5 parts with highest energies, peak impact force, maximum strain in product and general behavior of product during impact especially the motion of internal parts of washer and dryer.

Back Edge Impact Results Summary

Top 5 Parts with Highest Internal Energies

1. Bottom-foam
2. Corrugatedboard-main
3. Pretension_spring
4. Cabinet_CW2?
5. Corrugatedboard-sheet

Peak G level = below 9.5 G’s
Observation: Peak recorded at front, top left accelerometer location

RMS Wall Force

\[ F_{RMS} = \text{below} \ 1000.0 \ \text{lbs} \]

Maximum Strain in Product = below 0.8%

Figure 7: Typical Computer Simulation Results Summary Report.
The results of the simulation were studied in detail using an onion peel method within the HyperView results post processor where it is possible to turn off one part at a time in order to see the performance of internal components deep within the product. This method was very effective in studying the amount of energy absorption shared between the product and package for all of the load cases. It is also possible to slow down or stop the impact animation in order to better understand impact event sequences of all relevant components. Product structure enhancements were made from baseline results by reviewing strains and energies of critical structure and these design improvements were then incorporated in the next design level. Figure 8 shows visible damage to the product during testing with confirmation from computer simulation. Product structure optimization was not part of this study but is recommended to be carried out together with package optimization. The overall performances of baseline simulations correlated very well with that of the test. Although the simulations did not account for accumulated damage on product or package as would occur during testing, it was possible to identify damage-causing load cases from the computer results. Figure 9 shows the correlation between test and computer simulation for the transportation tie down rod mechanism deformation.

![Test Deformations](image1.png) ![Simulation Deformations](image2.png)

**Figure 8: Product Damage During Test with Simulation correlation.**
Phase 4: Package Topology Optimization

Topology optimization using Altair® OptiStruct and Altair® HyperStudy was utilized to improve product protection, reduce material costs, reduce packaging weight and improve performance of both the EPS foam structures and the laminated paper corner posts. Since these structures have different purposes and functionalities, separate topology optimization models were created for the EPS foam and corner posts.

For the EPS foam structure topology optimization, a simplified FE model of the product structure with an accurate product mass was created, and the remaining space between the product and corrugate box was filled with design space, see Figure 10. The design space is all the material the computer optimization solver is allowed to consider or discard in order to meet predefined constraints and objectives. For the foam, the objective was to absorb the maximum amount of energy which in turn would reduce the transfer of energy into the product. Static equivalent loads were derived from the dynamic simulations from Phase 3 and all of the critical load cases were considered during the optimization process.
Several variations of constraints and objectives were considered during the topology optimization to get a better understanding of how to optimize the foam structures. Most of the results placed material along the perimeter and edges of the product where the product’s strength and rigidity is highest. An example of topology optimization results is shown in Figure 11.

Figure 10: Simplified FEA Product and Topology Design Space

Figure 11: Topology Results Using 10% Volume Fraction Density Plot.
These results were then interpreted into CAD and inserted back into the dynamic simulation models for verification. All the dynamic load cases were reanalyzed with the optimized foam structures and the resulting performance was compared to the baseline structures and project objectives. The CAD interpretation was modified several times to improve the foam’s performance further. An example of CAD interpretation is shown in Figure 12.

![Figure 12: CAD interpretation of Topology Results](image)

The corner post optimization was performed by only modeling the corner post itself. Furthermore, a reduction in the length was deemed plausible since the cross-section through the length of the corner post had to be constant. The optimization was set up to maximize axial stiffness since the main purpose of the corner posts was to carry the stacking loads. Equivalent static side loads from the impact analyses were also applied to the corner post topology optimization model. Figure 13 shows optimization FEA model with design space.

The design space for the corner post was constrained by the outer dimensions of the product and maximum corrugate box size. Static loads were calculated from applicable dynamic load cases and applied to the model. These loads needed to be scaled based on the number of corner posts that would physically share the load and the vectors were orientated based on the drop angle.
Several design space volume fractions were analyzed, but the objective was always to create the stiffest structure possible with the allotted material (design space). Corner post density plot results from the topology optimization are shown in Figure 14.
When creating a CAD interpretation from the topology results, manufacturing constraints were discussed and considered. A major constraint is that the corner posts are created from a laminated paper tube so the design had to be a closed loop and tight corners were difficult to manufacture. At this stage, the laminated paper thickness was kept consistent with the baseline thickness. The CAD interpretation of the corner post result is shown in Figure 15.

![Figure 15: CAD Interpretation of Corner Post](image)

**Phase 5: Package Size and Shape Optimization**

The optimized corner post design developed from the topology results was further optimized using size and shape optimization. More specifically, material thickness and cross-sectional shape of the corner post was optimized based on the results of critical static and dynamic simulations that were all incorporated into a single optimization run. The critical load cases within these simulations included the dynamic, front side impact and right side impacts, as well as the static stacking load case that included buckling. The optimization problem was set up as follows:

- Minimize the peak force on the dynamic right side impact
- The peak force on the front side impact was restricted
- Buckling factor was constrained to be above 1.0 for static stacking
- The laminated paper thickness is allowed to vary between 0.07" - 0.20"

Shape variables were setup within the optimization to allow the cross-sectional shape to change in order to improve the performance, Figure 16 shows an example corner post shape variables applied.
The size and shape optimization run produced a new cross-sectional shape with reduced thickness. A final comparison of the corner post design before and after size and shape optimization was made to quantify design performance improvements. The simulated peak reaction force shown in Figure 17 below measured for the right side impact was reduced from 6,206 lbs to 4,863 lbs (22% reduction).

Figure 16: Example of Corner Post Shape Variables

Figure 17: Right Edge Corner Post Impact Reaction Force Comparison
The buckling load capacity of the new design for static stacking was found to be 3.36 (635.04 lbs per corner post), which was slightly greater than the 3.10 buckling load capacity (585.90 lbs per corner post) of the previous iteration, and was significantly greater than the 2.60 buckling load capacity (491.40 lbs per corner post) of the baseline corner post. The optimized thickness of the corner post was 0.075 inches. Finally the perimeter length of the optimized corner post cross-section was 16.31 inches.

During the entire design cycle, the improvements of the packaging performance were very significant for the load cases that were analyzed. The maximum acceleration levels experienced by the product were reduced by 29.24% and the maximum product strain was decreased by 27.95%, Table 2 shows a summary of results comparisons between baseline and optimized package structure. Further improvements can be made to the packaging with further studies. Sufficient confidence was achieved in the methodology and technology to allow transfer to the engineers at Mabe for continued studies and improvements.

<table>
<thead>
<tr>
<th>Impact Loadcases</th>
<th>Baseline vs. Optimized Comparison</th>
<th>% Change in % Reduction in</th>
</tr>
</thead>
<tbody>
<tr>
<td>Straight Drop (3)</td>
<td>-5.8 %</td>
<td>-16.6 %</td>
</tr>
<tr>
<td>Front Side (1)</td>
<td>-29.2 %</td>
<td>+28.0 #</td>
</tr>
<tr>
<td>Right Side (2)</td>
<td>-23.7 %</td>
<td>-61.4 %</td>
</tr>
<tr>
<td>Back Side</td>
<td>-17.1 %</td>
<td>+11.26 #</td>
</tr>
<tr>
<td>Front Edge</td>
<td>+22.5 *</td>
<td>-8.7 %</td>
</tr>
<tr>
<td>Back Edge</td>
<td>-6.0 %</td>
<td>-28.8 %</td>
</tr>
<tr>
<td>Left Edge</td>
<td>-3.1 %</td>
<td>+18.0 #</td>
</tr>
<tr>
<td>Front Left Corner</td>
<td>-14.6 %</td>
<td>-24.9 %</td>
</tr>
<tr>
<td>Back Left Corner</td>
<td>-33.9 %</td>
<td>+47.8 #</td>
</tr>
</tbody>
</table>

* = Actual g level magnitude lower than baseline
# = Actual strain magnitude lower than baseline
(1) = Worst Loadcase for product damage
(2) = Second worst loadcase for product damage
(3) = Third worst loadcase for product damage

Table 2: Baseline and Optimized Results Comparisons.

4.0 Technology Transfer

Altair ProductDesign’s technology transfer program was applied throughout this project starting at the initial project planning stages. The program allowed Mabe to pilot this program and receive high level support in order to make sure the tools are used effectively and accurately with the added benefit being that this knowledge grows and resides in-house at Mabe. Three engineers from Mabe participated on this project (two engineers from test department and one from CAE department). The highlights of this program were providing class room type hands on training on
basic FEA course, pre-processing, analysis, post processing, product part selection for simulation, FEA model generation and meshing, load case set up, material selection, material correlation with simulation, results evaluation and finally a written exam. Technology transfer was achieved successfully given the tight schedule and project timelines. A total of three one-week long visits took place during this project, two at Mabe and one at Altair ProductDesign’s facilities. Most of the technology transfer took place on regular conference calls and WebEx meetings. As with most technology transfers programs, the flow of information and knowledge was bi-directional.

5.0 CONCLUSIONS
By applying a structured approach to optimizing packaging structure layout and design, significant performance improvements were noticed with the resulting optimized design. Eight out of the nine load cases had reductions in peak ‘g’ levels ranging from 3.06% to 29.24%. The top three worst load cases were front side, right side, and straight drop. These three load cases improved significantly with respect to predicted ‘g’ levels in the optimized design. Load case front edge had its peak ‘g’ level increase by 22.47%, however this was not an issue as the actual peak ‘g’ is still relatively low and is not the dominating load case. It is worth noting that the complete ‘g’ pulse needs to be studied as was done in this analysis and not only the peak levels in order to determine performance improvements. The maximum strains predicted in the product also were much lower than the baseline for most of the load cases. Load case front side had the highest baseline strains at 8.98% and these strains were reduced by 27.95% in the optimized design. This load case is still the dominating load case for the optimized design in terms of maximum strain on product. Although strains increased for some of the other load cases, the actual strain values were lower than front side load case. The optimized corner post design shows an increased resistance to buckling in stacking as well as improved energy absorption capabilities in side impact simulations. Figure 18 shows foam structure differences between baseline and optimized designs. Figure 19 shows baseline design and an example of optimized corner post cross section shapes with performance data.
Figure 18: Baseline and Optimized Foam Structure

Figure 19: Baseline and an example of Optimized Corner Post Design
Application of simulation methods to package design has provided Mabe engineers greater insight into the physical behaviour of the product and packaging during dynamic impacts. Additional load cases, further packaging optimization and the effect of environmental conditions can be evaluated in future studies. In addition, Mabe can perform what-if studies on the product-packaging system to identify critical areas for damage avoidance. As a result of this process, Mabe CAE and Test engineers can apply CAE simulation methods on future products to improve packaging and product structure. The business benefits to using CAE include reduced time-to-market, lower prototyping costs, less physical testing and improved product performance. Mabe’s packaging process also requires establishing cost objectives for product packaging. It is expected that the application of CAE for their package development will help to identify cost savings both in material selection and usage.