A COMPARISON BETWEEN EXPERIMENTAL TESTING AND NUMERICAL SIMULATIONS OF IMPACT LOADING ON ALUMINUM AND MAGNESIUM STEERING WHEEL ARMATURES

William J. Altenhof
The University of WindsorDepartment of Mechanical, Automotive, and Materials Engineering
401 Sunset Avenue
Windsor, Ontario, Canada
N9B 3P4
E-mail:altenh1@uwindsor.ca

William D. Ames
K.S. Centoco Limited
Design and Development Engineering
2450 Central Avenue
Windsor, Ontario, Canada
N8W 4J3
E-mail:kscentoc@mnsi.net

Abbreviations:
mm - millimetre(s)
in - inch(es)
FE - finite element
BDC - bottom dead centre
TDC - top dead centre
LVDT - linear voltage differential transducer

Keywords:
impact testing
steering wheel armature
aluminum
magnesium

A COMPARISON BETWEEN EXPERIMENTAL TESTING AND NUMERICAL SIMULATIONS OF IMPACT LOADING ON ALUMINUM AND MAGNESIUM STEERING WHEEL ARMATURES

by

William Altenhof and William Ames

ABSTRACT

In the present automotive industry, all corporations are focusing on developing automobiles which are light weight, fuel efficient, conform to a level of safety outlined by government regulations, and are available to the consumer at a reasonable cost. The automobile industry has placed a significant amount of time and research funding into developing vehicles which can meet these requirements.

K.S. Centoco Ltd., a steering wheel manufacturer, located in Windsor, Ontario, Canada, has developed a testing machine to investigate collisions occurring with steering wheels. This machine considers several experimental parameters in impact testing while providing a large amount of information to be obtained in an experiment. Experimental testing was conducted on a four spoke steering wheel armature which is manufactured from a magnesium alloy. In an effort to compare the structural worthiness of magnesium and aluminum alloys in an impact situation, the identical armature was fabricated from a proprietary aluminum alloy and impact experiments were also conducted with the geometrically identical aluminum armature.

Numerical simulation of the experimental process has also been conducted using LS-DYNA. Detailed four spoke steering wheel armature finite element models (employing both magnesium and aluminum alloys) have been developed and simulated under similar conditions which were conducted experimentally. Comparisons between experimental tests at six different impact situations with collisions between the steering wheel armature and a rigid plate are presented in this paper. As well, comparison of the finite element model is considered by investigating changes in the element formulation associated with the armature.

The experimental and numerical observations indicate that the predictive capabilities of the aluminum material model are better developed than the magnesium material model. In addition, selection of the finite element formulation significantly affects the numerical results.

INTRODUCTION

In 1997 K.S. Centoco Ltd., in conjunction with the University of Windsor, developed a testing machine for impact loading on steering wheels. The machine development was based upon current and past standardized steering wheel testing procedures, most specifically, Directive 74/297/EEC from Europe [1] and the Society of Automotive Engineers SAE J944 from North America [2].

Both the above mentioned standards utilized a common deformable chestform (bodyform) with specific material and mechanical properties identically outlined in both testing standards. To isolate the energy absorption characteristics of only the steering wheel armature the deformable chestform was replaced with a non-deformable, and hence non-energy absorbing, plate.

Impact testing (both numerically and experimentally), with collisions occurring between the rigid plate and the magnesium and aluminum armatures, was conducted to investigate the predictive capabilities of the two different FE models and the energy absorption characteristics between the two geometrically identical magnesium and aluminum armatures. This paper considers only the comparison between experimental and numerical testing of the aluminum and magnesium armatures.

Terminology Associated with Steering Wheel Testing

Steering Wheel Armature. The steering wheel armature is the skeleton of the steering wheel. It supports all components of the steering wheel (airbag, driver controls, etc.) and is the most significant structural component of the steering wheel.

The Column Angle. The column angle represents the angular displacement from a horizontal reference line to the centre line of the steering column. Figure 1 illustrates a steering wheel and a bodyform which are used to define the column angle. In measuring the column angle, positive values are taken in a clockwise sense from the horizontal reference line. Furthermore, a zero degree column angle represents the centre line of the steering column in line with the horizontal reference line.

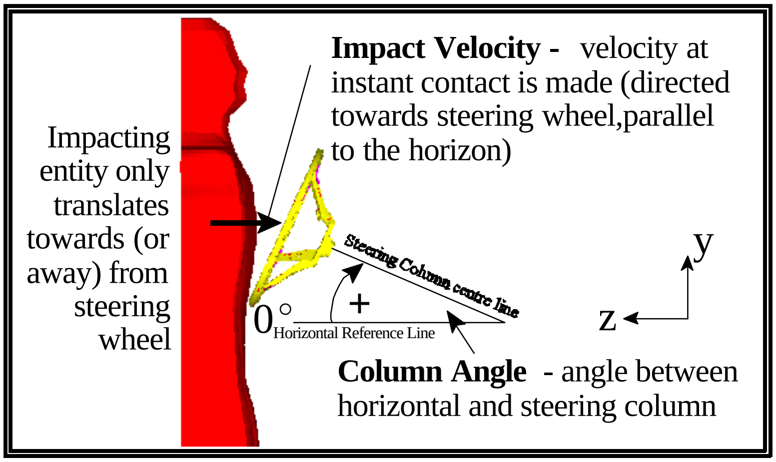

Figure 1. The column angle and impact velocity.

Typically, in modern automobiles the column angle ranges from 25 degrees to 35 degrees. However, with the addition of tilt steering, the actual column angle, referenced to the steering wheel, may not be the actual column angle specified by the automobile manufacturer. Depending upon the preference of the driver, the column angle referenced from the steering wheel may be significantly different from the actual column angle. In all experimental and numerical tests the column angle was set at twenty five degrees (25°). The droptower testing machine uses gravity to accelerate the dropping entity onto the steering wheel armature. In this investigation three different dropping heights were considered 7 inches (178 mm), 14 inches (356 mm), and 21 inches (533 mm). These dropping heights developed impact velocities of 3.93 mph (1.76 m/s), 5.35 mph (2.39 m/s), and 6.58 mph (2.94 m/s) respectively. The combination of low impact velocities (less than 3 mph) and the massive dropping assembly, which has a weight of 126 lbf (or mass of 57.2 kg), provided a means of significantly deforming the steering wheel armature.

The Wheel Angle. This angle represents the orientation or angular displacement which the steering wheel is being turned during an impact test. Figure 2 illustrates the wheel angle and different wheel angle locations over the entire steering wheel. The wheel angle is commonly measured using an identical approach to that of an analog clock, or in degrees. The wheel angle varies from the 12 o clock position (0° position), which is the top dead centre (TDC) of the steering wheel (in normal driving conditions, i.e. driving straight ahead), to the 6 o clock position (180° position), which is the bottom dead centre (BDC) of the steering wheel (in normal driving conditions), and back to the 12 o clock position.

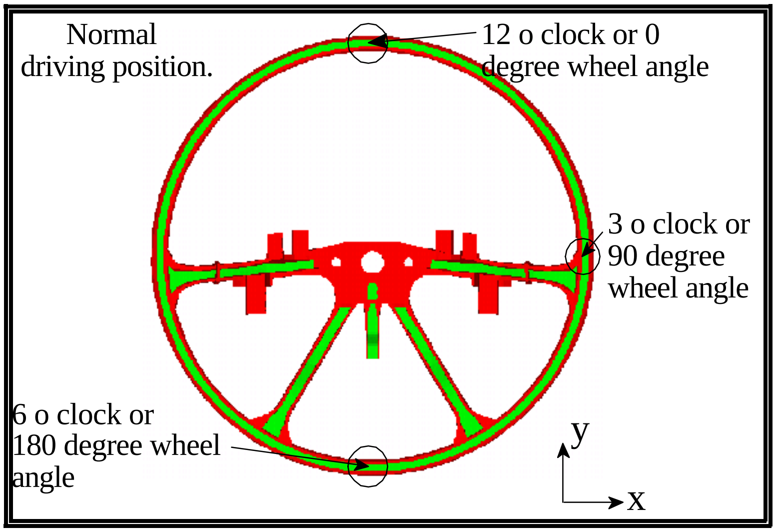

Figure 2. The wheel angle.

It should be noted that any collision between the rigid plate and steering wheel always occur at the BDC of the steering wheel. However, depending upon how the steering wheel is turned, this may not represent the 6 o clock (180°) position. If the wheel is turned, then in general, impact will not occur at the 6 o clock position. In addition, all impacts on the armature occur along the midline of the armature.

APPROACH

Experimental Impact Testing Procedure

The testing machine uses gravity to develop a relative velocity between the rigid plate, which is mounted to an aluminum crosshead, and the 4 spoke steering wheel armature. The plate free-falls from a chosen dropping height to produce the corresponding impact velocity, while the armature is securely fastened to a mounting device which is connected to a triaxial load cell. Figure 3 illustrates the testing apparatus.

As previously mentioned, the three different dropping heights selected for this investigation were 7 inches (178 mm), 14 inches (356 mm), and 21 inches (533 mm). In addition, two different wheel angles were considered in this study. Three tests (at the above mentioned dropping heights) were conducted with impact occurring and the 6 o clock position of the armature. Three additional tests were conducted in which impact (at the three different dropping heights) occurred at the 3 o clock position. In total, six different testing situations were investigated, these are summarized in Table 1. Overall, twelve tests were conducted experimentally (six for the aluminum based armature and six for the magnesium based armature).

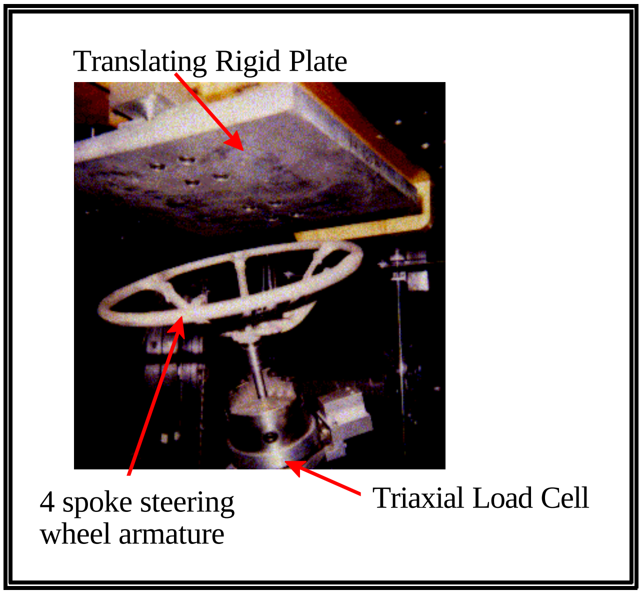

Figure 3. Experimental testing apparatus.

Table 1. Summary of Six Different Testing Conditions

Testing Condition #	Column Angle (degrees)	Wheel Angle (o clock position)	Drop Height (inches/millimetres)
1	25°	6 o clock	7 in. / 178 mm
2	25°	6 o clock	14 in. / 356 mm
3	25°	6 o clock	21in. / 533 mm
4	25°	3 o clock	7 in. / 178 mm
5	25°	3 o clock	14 in. / 356 mm
6	25°	3 o clock	21in. / 533 mm

The most significant experimental observations, which are compared with LS-DYNA simulations, were identified to be the loading profile, in the direction of the impact velocity, as a function of crosshead displacement. As previously mentioned, a triaxial load cell is mounted below the armature for determination of impact forces between the rigid plate and the steering wheel armature. A linear voltage differential transducer (LVDT) is rigidly mounted to the side of the crosshead for determination of displacement during an impact test.

Development of a Steering Wheel Armature Finite Element Model

Finite Element Geometry. Dimensions of the four spoke steering wheel armature were provided from K.S. Centoco. A detailed FE model consisting of two parts was developed. Due to the geometry of the armature, certain cross-sectional dimensions were too small to supply enough underintegrated finite elements (solid element formulation #1,[3]) through the thickness of the sections. At a minimum, four underintegrated elements where employed through all sections of the armature. In areas where this minimum number of elements caused excessively small dimensions of the finite elements, the degree of discretization was decreased and a selectively reduced integrated element was used (solid element formulation #2). Initially, all simulations were conducted with a selectively reduced integrated element, however in an effort to lower computational time, the effect of an underintegrated element was investigated for the part which contained at least four through thickness elements (this was implemented for Testing Condition Numbers 3 and 6 only). The total number of solid elements within the armature model were 9696 hexahedral elements and 390 wedge elements. Figure 4 illustrates the FE model of the four spoke steering wheel armature.

The rigid plate was modeled using the Belytschko-Tsay shell element, with length and width dimensions identical to the actual experimental rigid plate. The thickness (or depth) of the shell element was specified as unity and the density of the plate was modified to take into account the difference in geometry while still simulating the total mass of the actual experimental plate. A total of 2500 shell elements were used in the rigid plate FE model.

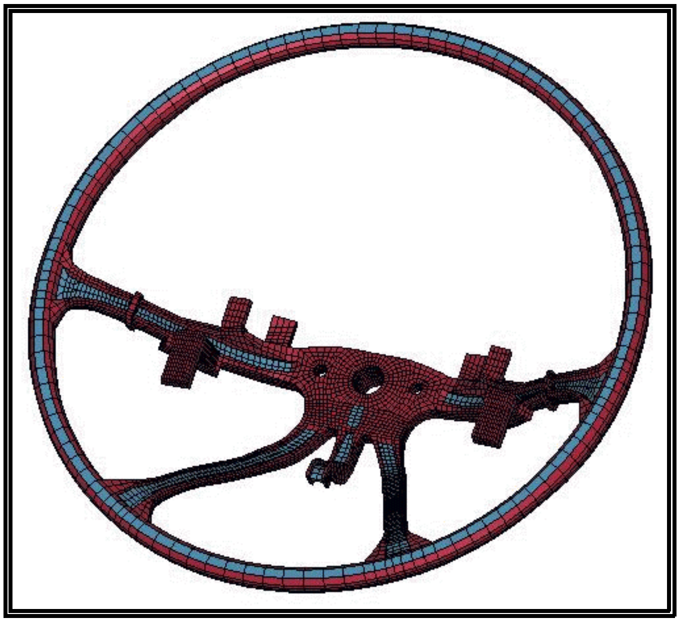

Figure 4. Finite element model of the 4 spoke armature.

Material Modeling. The four spoke steering wheel armature, which was experimentally tested, was fabricated from two different materials; aluminum and magnesium alloys. Both material models use Material type 24 (MAT_PIECEWISE_LINEAR_PLASTICITY). Stress versus effective plastic strain curves were developed (from quasi-static tension tests) and used in both the material models. The Cowper-Symonds strain rate parameters for the aluminum alloy were provide from Jones [4]. The Cowper-Symonds strain rate parameters for magnesium alloys could not be found even though literature regarding the effect of strain rate on the mechanical properties of this alloy exists [5].

Modeling for Contact. A single contact algorithm (CONTACT_NODES_TO_SURFACE) was implemented for impact between the armature and the rigid plate. A part set was developed for the two different parts of the armature and incorporated into the contact algorithm as the slave nodes.

DISCUSSION OF RESULTS

Experimental / Finite Element Model Comparison

Vertical loading profile as a function of crosshead displacement. The experimental and numerical vertical load versus crosshead displacement curves for the aluminum armature are presented in Figures 5 through 10. The vertical load versus crosshead displacement curves (experimentally and numerically) for the magnesium armature are illustrated in Figures 11 through 16.

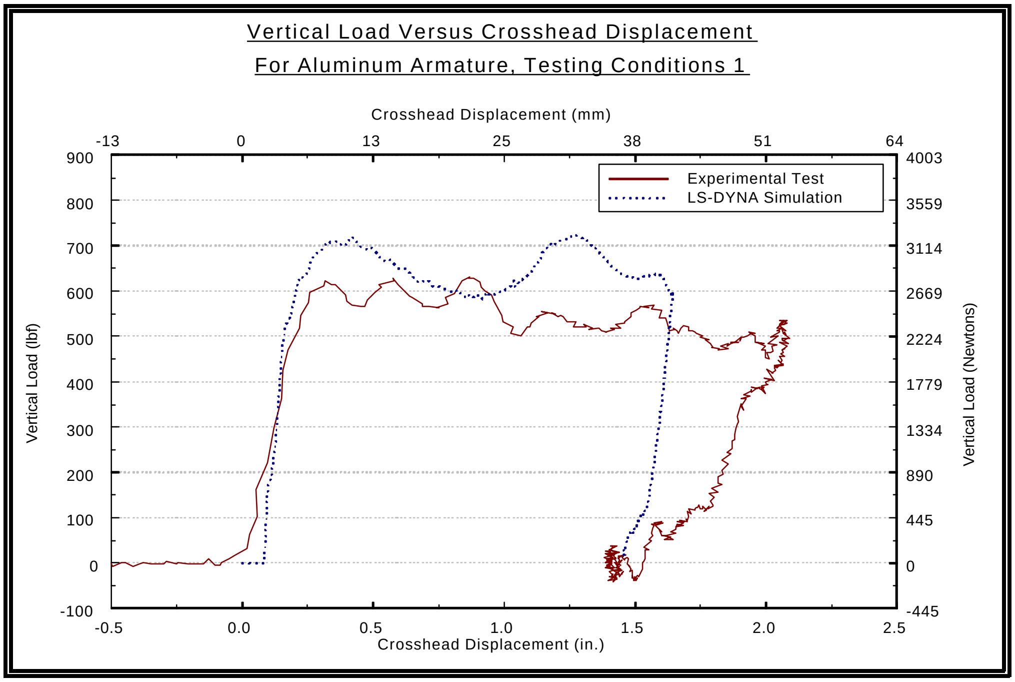

Figure 5. Load versus displacement for the aluminum armature under testing condition 1.

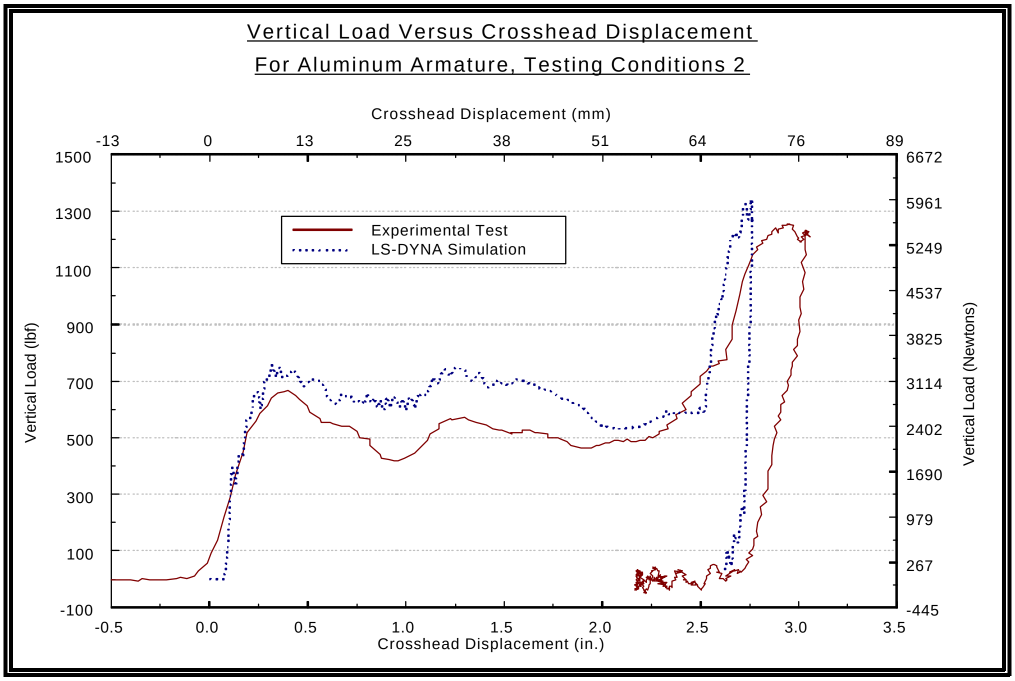

Figure 6. Load versus displacement for the aluminum armature under testing condition 2.

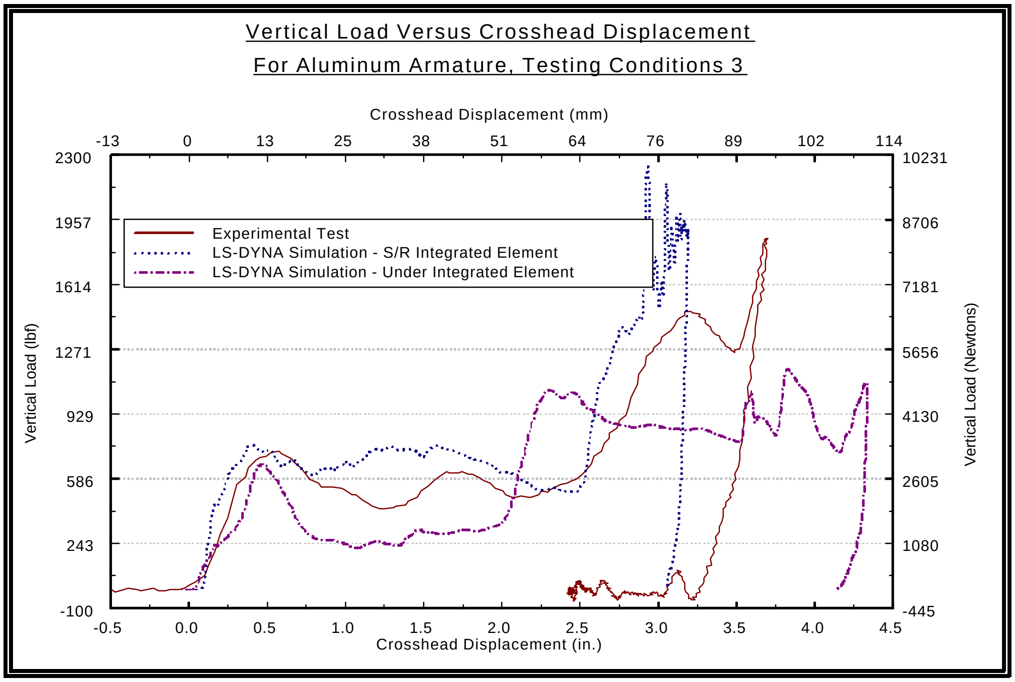

Figure 7. Load versus displacement for the aluminum armature under testing condition 3.

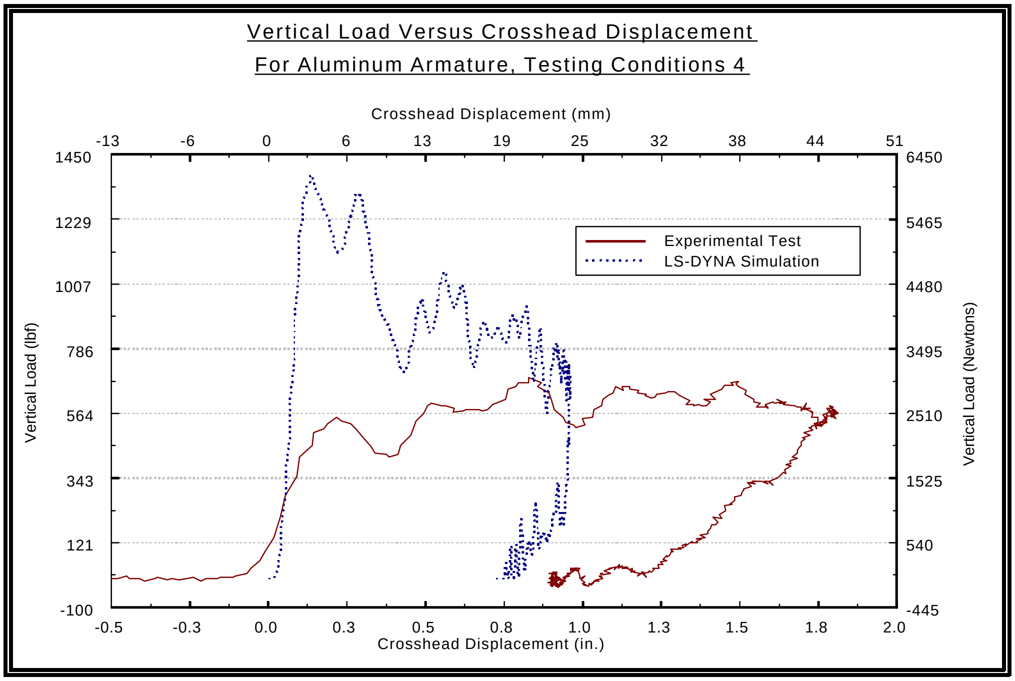

Figure 8. Load versus displacement for the aluminum armature under testing condition 4.

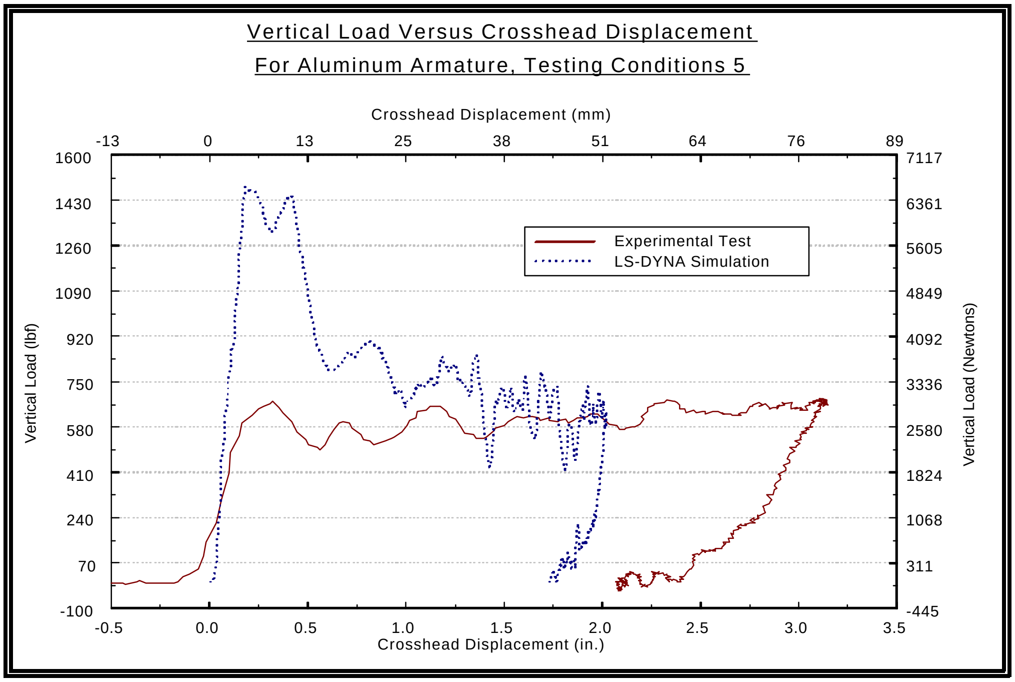

Figure 9. Load versus displacement for the aluminum armature under testing condition 5.

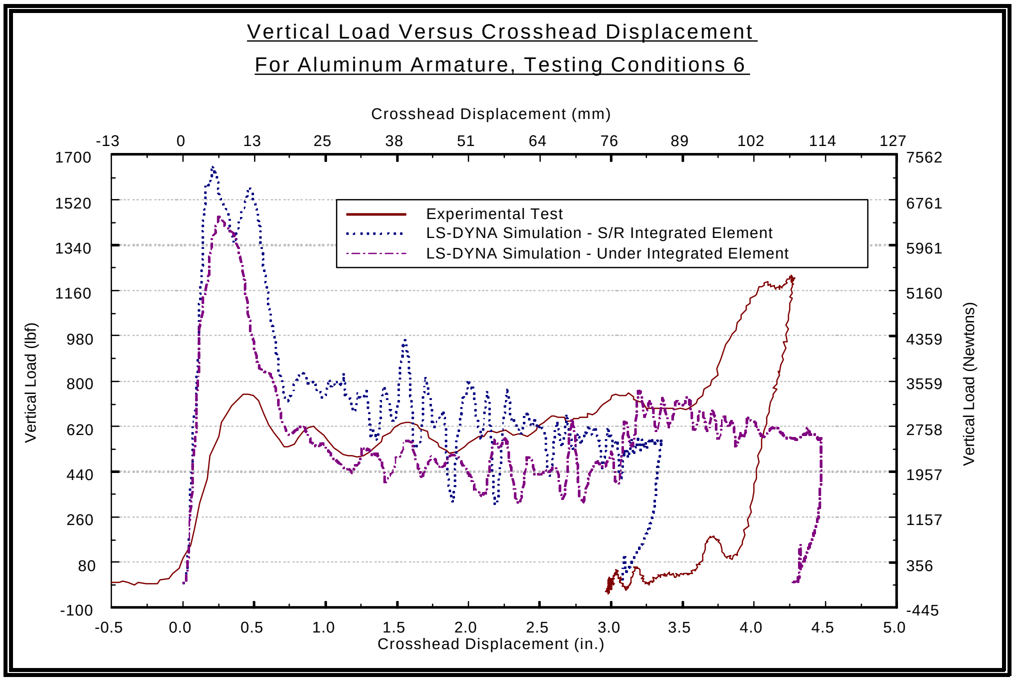

Figure 10. Load versus displacement for the aluminum armature under testing condition 6.

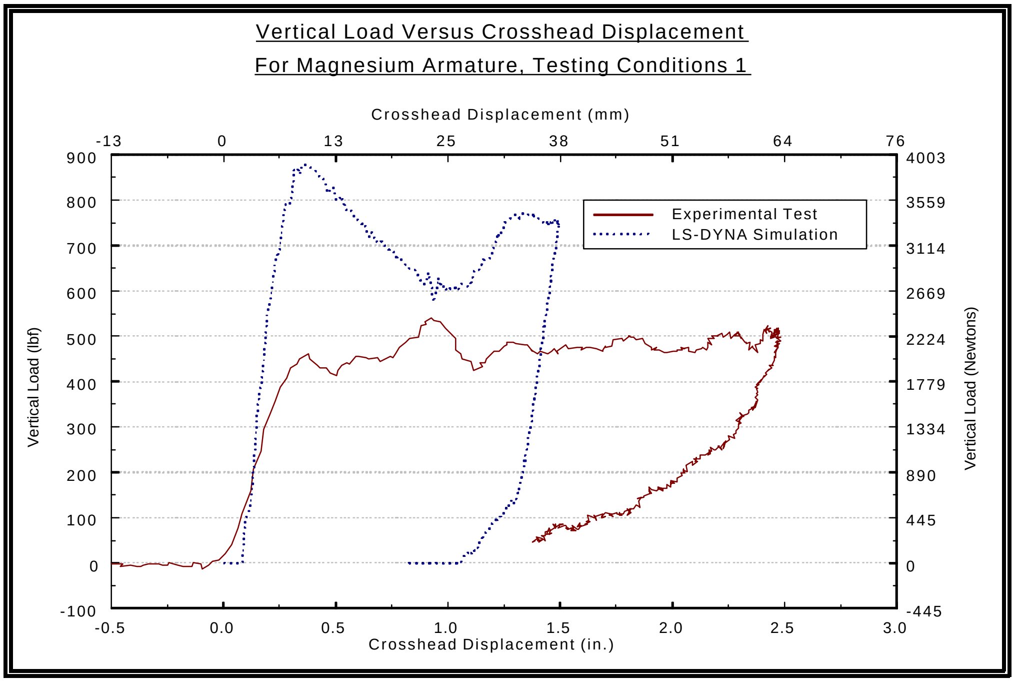

Figure 11. Load versus displacement for the magnesium armature under testing condition 1.

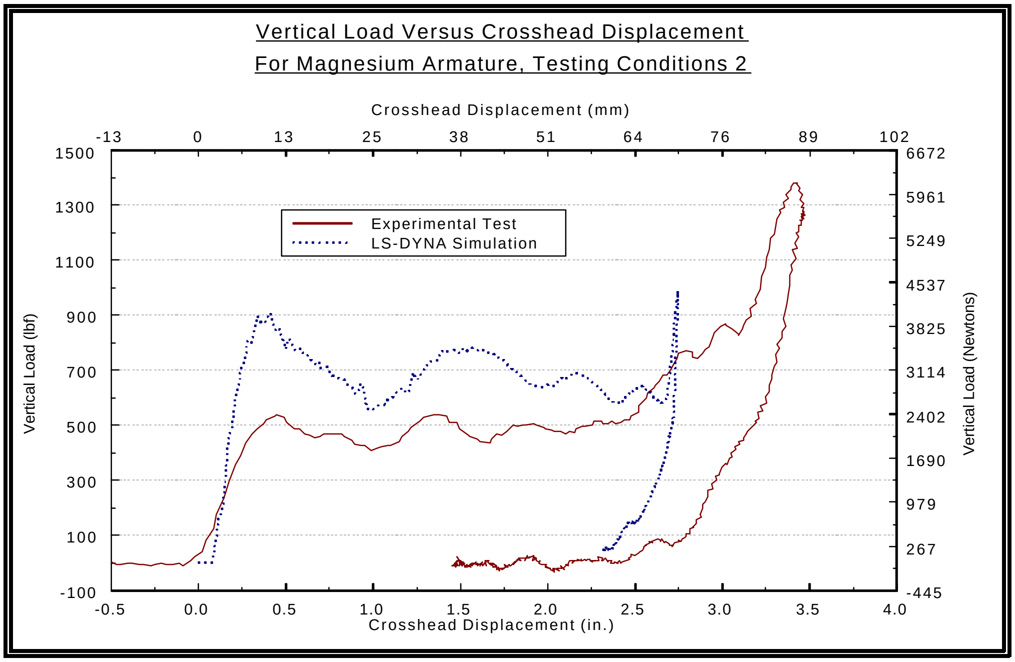

Figure 12. Load versus displacement for the magnesium armature under testing condition 2.

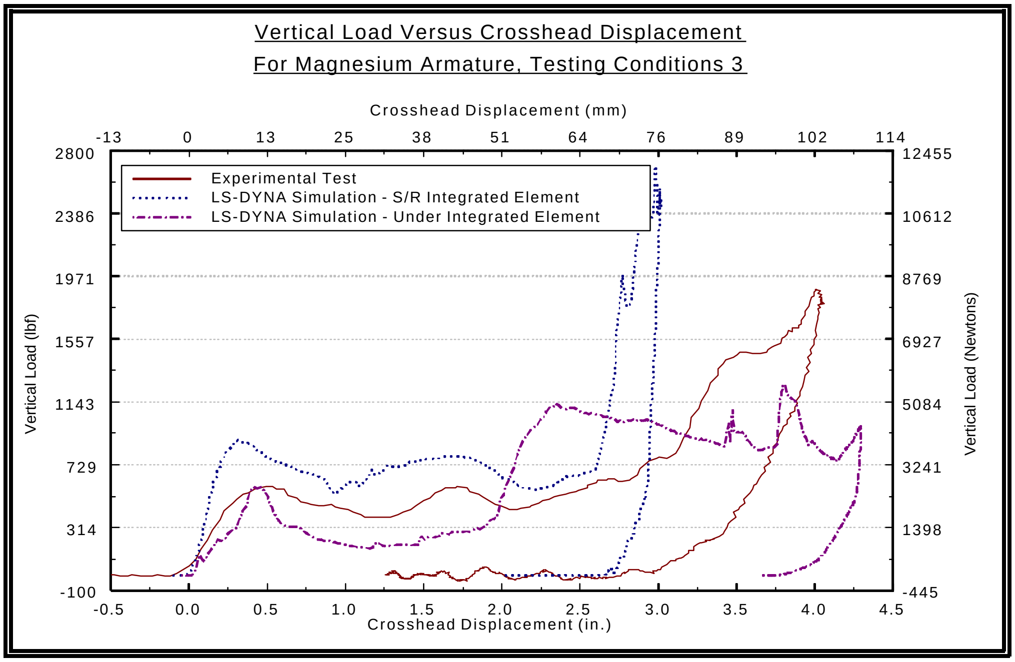

Figure 13. Load versus displacement for the magnesium armature under testing condition 3.

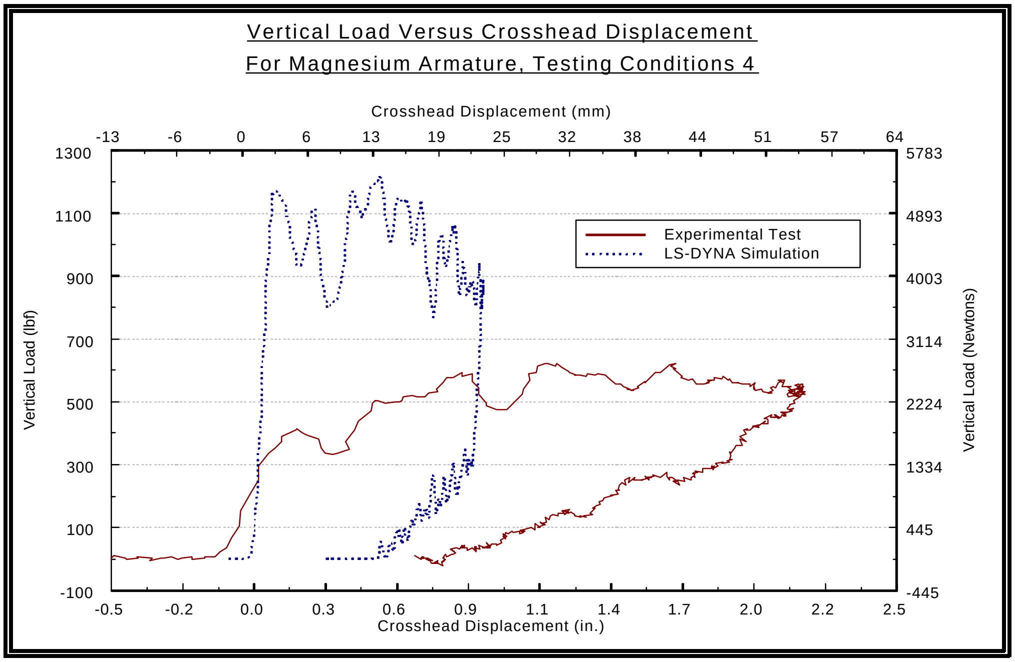

Figure 14. Load versus displacement for the magnesium armature under testing condition 4.

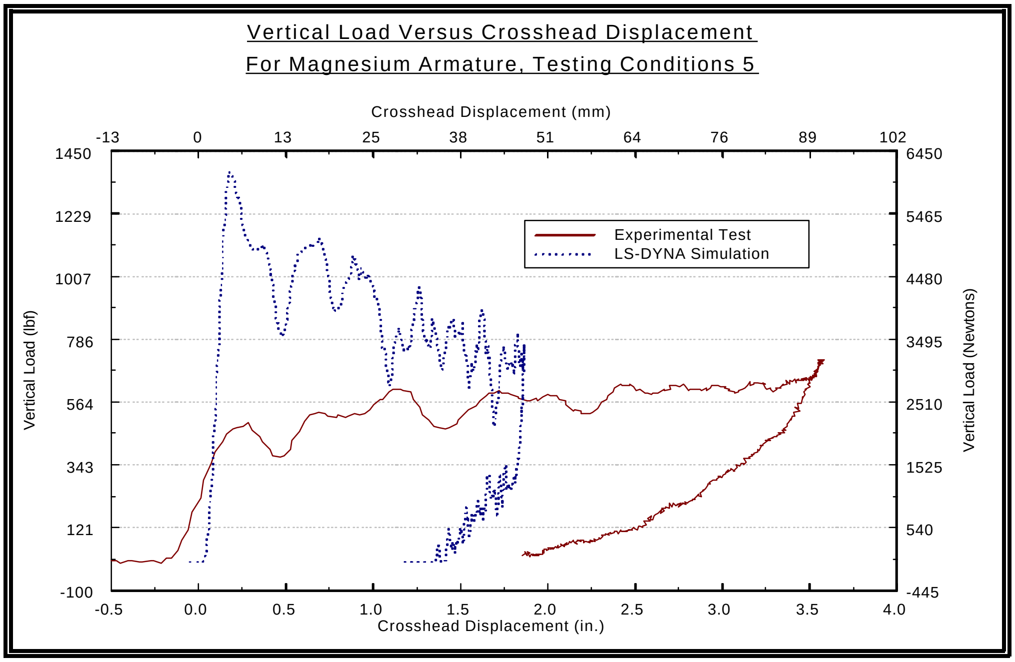

Figure 15. Load versus displacement for the magnesium armature under testing condition 5.

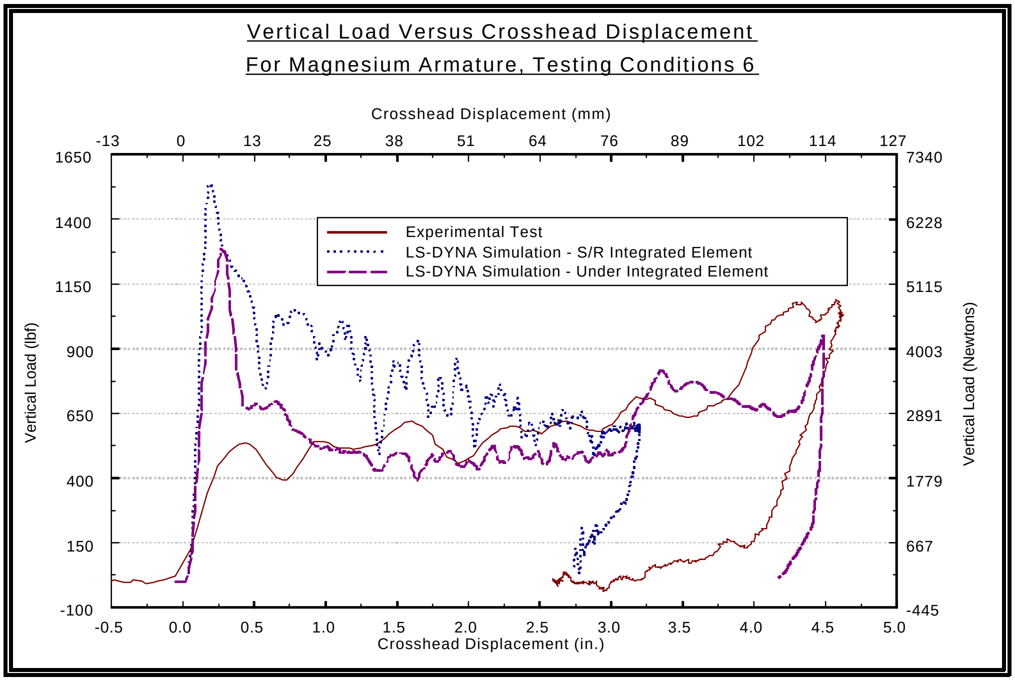

Figure 16. Load versus displacement for the magnesium armature under testing condition 6.

Discussion of Results from Experimental Testing and Numerical Simulations

Testing Conditions 1 through 3. The vertical loading profiles from the numerical simulations (illustrated as a function of the crosshead displacement) show that a higher degree of experimental predictability exists for the aluminum material model. An excellent correlation between experimental testing and numerical simulations exists for testing conditions 1 through 3 for the aluminum material model when employing a selectively reduced integrated element formulation in the FE model of the armature. Testing conditions 1 through 3 for the magnesium material model (and utilizing a selective reduced integrated element) illustrate that the FE model behaves considerably more stiff (higher loads and lower displacements) then the experimental observations.

When using an underintegrated element formulation in the FE model of the armature (for testing condition 3 and either material model) the simulation results predict a less stiff steering wheel structure. This should be expected as higher order integration will capture higher order terms in the stiffness matrix [6].

Testing Conditions 4 through 6. Observations from testing conditions 4 through 6 show that both material models (when using a selective reduced integrated element) predict a significantly stiffer structure than results obtained from experiments. For these testing conditions no significant difference, in predictive capabilities, between the aluminum and magnesium material models is observed. Implementing an underintegrated element formulation with either material model (for testing conditions 4 through 6) does aid in better predicting experimental findings.

Difficulties Modeling Magnesium Alloys. Research has shown that there is a strong effect of processing conditions on the mechanical properties of magnesium alloys [7, 8]. In addition, past mechanical testing conducted by K.S. Centoco has also shown that a significant variation in mechanical properties of the magnesium alloy (AM50) exists for specimens die-cast in similar environments. There is a high degree of difficulty in developing mathematical material models of the magnesium alloy when a significant variation in material properties is experimentally observed. Hence, a lower predictive capability in the numerical simulations should be expected as was observed for testing conditions 1 through 3.

In addition, the crystalline structure of magnesium causes the alloy to behave in an anisotropic behaviour. However, material model type 24 (MAT_PIECEWISE_LINEAR_PLASTICITY) assumes that the mechanical material properties are independent of direction within the structure. This would induce error in the numerical modeling of magnesium and may be influencing the numerical results which illustrate a lower degree of experimental predictability.

In addition, an inhomogeneous structure occurs for die cast specimens. The die cast armatures contain a skin of dense small grains on its outer surface and an inner section which is considerably more porous. Inclusions and defects are generally pushed to the inner porous core overall resulting in a highly non-homogeneous structure. All FE analyses are based upon the assumption that a homogeneous structure exists for the material model. The fracture toughness of magnesium alloys is less than the toughness of aluminum alloys [9]. The resulting non-homogeneous structure, from the die-casting process, and the lower fracture toughness of magnesium will result in difficulties for numerically modeling the severe deformation of magnesium components. Although an inhomogeneous structure may also exist in the aluminum armature, the fracture toughness of the material is significantly better than magnesium and may be a factor in the better numerical and experimental testing correlation.

CONCLUSIONS

The focus of this investigation was to compare numerical and experimental observations from the impact loading of geometrically identical aluminum and magnesium steering wheel armatures. A comparison of the findings illustrated that, depending upon the testing conditions, the aluminum material model generally better predicted actual experimental results in terms of loading and displacement profiles. The magnesium model behaved structurally stiffer than the aluminum material model. In addition, the results obtained from the numerical simulations are very dependent on the selection of solid element formulation used in the FE model. Stiffer structural responses were found for FE models which utilized a selectively reduced integrated element compared to those models which used an underintegrated solid element formulation.

The predictive capabilities of the die-cast magnesium armature model are most likely influenced by the anisotropic behaviour of the material, the nonhomogeneous structure, and the inability to accurately experimentally determine mechanical properties of the alloy.

REFERENCES

[1]. Annex III to Directive 74/297/EEC. The European Economic Communities, (December 1991), pp.12-15.

[2]. Society of Automotive Engineers, Steering Control System - Passenger Car - Laboratory Test Procedure - SAE J944, 1992 SAE Handbook, Volume 4, Warrendale, PA., U.S.A., (1992), pp. 34.230-34.232.

[3]. Livermore Software Technology Corporation, LS-DYNA Keyword User s Manual Version 940, (June 1997).

[4]. Jones, N., Structural Impact, Cambridge University Press, Cambridge, United Kingdom, (1997), pp.349.

[5]. Carlson, B. E., The Effect of Strain Rate and Temperature on the Deformation of Die Cast AM60B, Society of Automotive Engineers (SAE) paper number 950425, International Congress and Exposition, (1995).

[6]. Cook, R. D., Finite Element Modeling for Stress Analysis, John Wiley & Sons Inc., Toronto, (1995).

[7]. Dow Chemical, S-N Curves for AZ91 and AM60, (1993).

[8]. Rodrigo, D., Murray, M., Mao, H., Brevick J., Mobley, C., Chandrasekar, V., Esdaile, R., Effects of Section Size and Microstructural Features on the Mechanical Properties of Die Cast AZ91D and AM60B Magnesium Alloy Test Bars, Society of Automotive Engineers (SAE) paper no. 1999-01-0927, International Congress and Exposition, Michigan (1999).

[9]. Courtney, T. H., Mechanical Behaviour of Materials, McGraw Hill Inc., Toronto, (2000).