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Effects of Mesh Size and Remapping on the Predicted Crush Response of Hydroformed Tubes

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ABSTRACT:

Crashworthiness simulations can be useful tools in vehicle design. According to Du Bois [1], there are many factors which affect the reliability of crashworthiness models. Especially, the mesh size and the mapping of forming results into crash models. Few studies have analyzed the mesh size effect with forming results on the crashworthiness of frame components. This paper presents an analysis of crush response of hydroformed aluminium tubes from both experiments and finite element simulations. The predicted crush response for tubes meshed with different mesh sizes for hydroforming with results transferred to the crash simulations will be firstly shown. Predicted mean crush forces will be compared to measured ones. Thereafter, forming results were remapped on a secondary model, having coarser mesh sizes for crush simulations, with the LS-DYNA option called *INCLUDE_STAMPED_PART. Results show that in certain instances, it may be better to use a fine mesh size for the hydroforming models and remap forming results to coarser mesh sizes for crashworthiness models to save computational time.

Keywords:
Crashworthiness, Crush, Energy absorption, Crush force, Remapping, Hydroforming, Aluminium, Mesh size

INTRODUCTION

The use of aluminium is actually increasing for the manufacture of automotive frame structures in order to reduce weight and fuel consumption. Moreover, forming methods are also developing in order to reduce the number of manufacturing steps and their associated costs. Some automotive manufacturers are now using the hydroforming process to manufacture specific structural frame components such as side members. According to Mortimer [2], the growing use of hydroformed parts may lead to increased strength and rigidity, weight and parts reduction. Those potential changes may, in turn when considered with a variety of other factors, suggest potential benefits in crashworthiness performance in certain instances. In a larger project involving General Motors, the University of Waterloo, Queens University and the Aluminium Technology Centre, the crush characteristics of hydroformed straight and S-rail aluminium tubes were studied.

The determination of the energy absorption of hydroformed tubes can be obtained by both experimental tests and finite element simulations. De Kanter [3] analyzed the crush characteristics of straight tubes experimentally and by using analytical and numerical methods. The numerical results agreed well with experimental ones but the analytical formulas gave limited accuracy. Grantab et al. [4], Oliveira et al. [5] and Zheng et al. [6] have successfully used the finite element method to evaluate the crush characteristics of pre-bent, hydroformed tubes. Williams et al. [7] evaluated the absorption energy of straight hydroformed tubes without end feed, accounting for the forming effects of strain hardening, residual stresses and thickness changes. Kirby et al. [8] observed an increase of the energy absorption of about 9 % for a hydroformed part during a crush simulation when the forming results were transferred using the **dynain** file. Cafolla et al. [9] have also shown that including forming results can have a considerable influence on collapse modes and energy absorbed of structural components.

According to Du Bois [1], in addition to including forming results into crush models, it is also necessary to use fine meshes to increase the reliability of crashworthiness simulations. However, the need of higher reliability results in an increase of size of numerical models. Forming simulations can generally be carried out with finer mesh size to predict adequate thickness and plastic strains distributions over the deformed geometry. Thereafter, forming data can be remapped on coarser mesh sizes in the crashworthiness model to save computational time. LS-DYNA has an option called

*INCLUDE_STAMPED_PART which remap forming finite element results from a fine mesh to a new coarser one.

This paper will firstly show the variation of energy absorption of tubes meshed with different mesh sizes for the hydroforming operation. Models developed for hydroforming with end feeding have already been validated by D'Amours et al. [10]. Forming results were then transferred to the crush characteristic models with the same mesh used for the hydroforming simulations. Predicted mean crush forces will be compared to measured ones. On a second analysis, one specific mesh size of 4x4 mm was used for the hydroforming operation and the forming results were remapped to the crush model with coarser mesh sizes.

NUMERICAL MODELS

TUBE AND DIE GEOMETRIES

Hydroforming experiments were performed on seam-welded 76.2 mm outer diameter, 3 mm thick AA5754 aluminium alloy tubes using a die system with end feed. The tubes were formed into a tube with a 76.2 mm square cross-section and a 6 mm corner-fill radius. The die used to hydroform aluminium tubes is shown in figure 1.

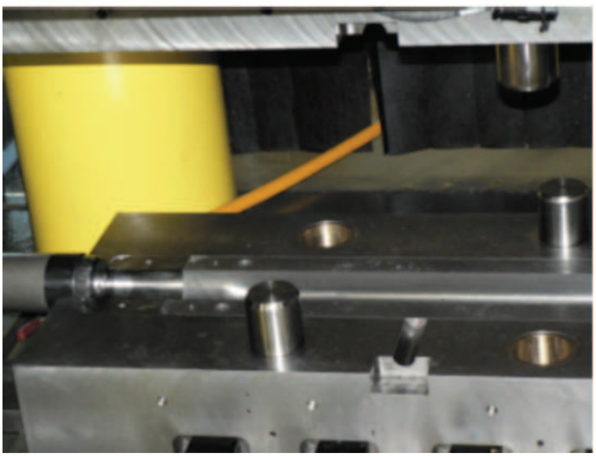

Figure 1: Die with removable insert for tube hydroforming

Finite element models of the tube hydroforming experiments were created using LS-DYNA. The die system, two plungers and the tube were modeled. Both the die and plungers were modeled using rigid shell elements. To analyze the mesh size effect on the absorption energy, different shell element sizes of 4x4, 6x6, 8x8 and 10x10 mm were considered for the tube. The Belytschko-Tsay type 2 formulation was used for the shell elements during the hydroforming simulations. A general surface to surface contact treatment was prescribed between the tooling and the tube with a static coefficient of friction of 0.045, determined from twist-compression testing.

The flow stress, $\bar{\sigma}$ versus effective plastic strain, $\bar{\varepsilon}$ used to describe the hardening behavior of the material in the simulations with the von Mises yield criterion was given by the following equation:

$$\bar{\sigma} = a - \left(a - \sigma_y\right)\exp\left(-b\bar{\varepsilon}^c\right) \qquad \text{(Eq. 1)}$$

where, the yield stress, σ_y was approximately equal to 100 MPa, and the constants *a*, *b*, and *c* were equal to 315, 5.5, and 0.77, respectively for stress units of MPa. This was based on tensile tests performed on as-tubed 3mm, AA5754 specimens. It should be noted, that anisotropy was not considered in the current results, but will be studied in future research.

SUCCESSIVE FINITE ELEMENT SIMULATIONS

To obtain realistic energy absorption during simulation of the crush events, it is important to incorporate the forming results into crush models. The method that is generally used in LS-DYNA is related to a file called **dynain** which includes mesh geometry, thickness, strain hardening, and residual stresses. In addition to the hydroforming and crush simulations, other ones such as the springback of the tube during the opening of the die, the creation of the crush beads and finally the tube trimming were also performed. The springback simulation of the hydroformed tube is carried out with the implicit solver of LS-DYNA and the full integration shell formulation 16. In this study, AA5754 tubes were hydroformed using 64 mm of end feed at each tube end. The crush models incorporated a rigid wall moving in the axial direction of the tube at an initial velocity of 7 m/s with a mass of 560 kg, crushing its free end. These values corresponded to the experimental parameters. The nodes of the other tube end were constrained in translation and rotation during the crush.

VALIDATION

Crush tests were performed by General Motors on aluminium tubes hydroformed at the Aluminium Technology Centre. A horizontal sled was used to crush two identical tubes at a time. Figure 2 shows the experimental setup with fixtures used to clamp the tubes in position. The tubes length available for crush was 350 mm. To easily initiate the first fold of the tube at the beginning of the crush test, crush beads (fold initiators) were incorporated along two opposing flat sides of the tube.

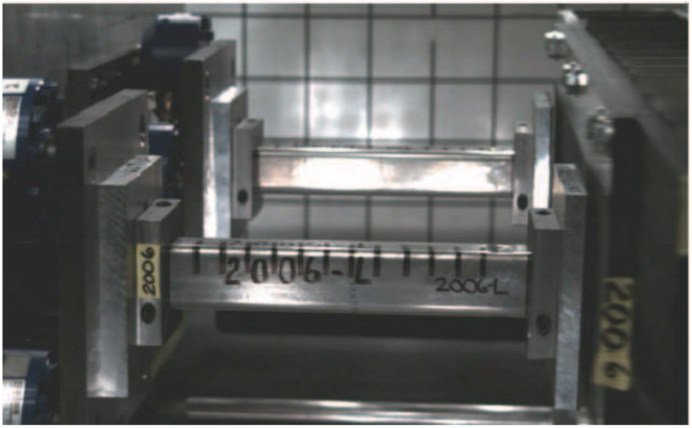

Figure 2: Clamping of hydroformed tubes for crash tests

The axial crush forces and distances were measured during the crush event for which these results are not presented in this paper. Instead, the results are presented based on the mean crush force versus distance which was determined by dividing the energy absorbed at a given distance, by the corresponding crush distance. The measured mean crush response of hydroformed tubes with a 6 mm corner-fill radius are shown in figure 3. Test results are repeatable. Also shown in figure 3, is the predicted mean crush force obtained with a mesh size of 4x4 mm for the overall successive finite element simulations which confirms that the models can adequately predict energy absorption.

MAPPING STRATEGIES

Two different mapping strategies with different mesh sizes are compared in this paper. The first analysis used the same mesh size for all simulations from hydroforming up to the crush with forming histories included using the **dynain** file. Four different mesh sizes of 4x4, 6x6, 8x8 and 10x10 mm were used for this analysis. The second analysis used the LS-DYNA option *INCLUDE_STAMPED_PART. Finite element results obtained after the springback simulation of the hydroformed tube with a fine mesh size of 4x4 mm were remapped on new coarser meshes of 6x6, 8x8 and 10x10 mm. For each coarser mesh, the remaining successive finite element simulations such as the creation of the crush beads, the tube trimming and the crush were then performed.

With the option called INCLUDE STAMPED PART, interpolation functions are used by LS-DYNA to remap the finite element solutions at each node and integration point of the old mesh towards the new nodes and integration points of a new mesh. More details concerning the keyword are provided by Hallquist [11]. For the crush simulations, the effect of this remapping was quantified by analyzing the variation of the energy absorption of the aluminium tubes. This was accomplished using a mesh size of 4x4 mm for the hydroforming and the springback simulations.

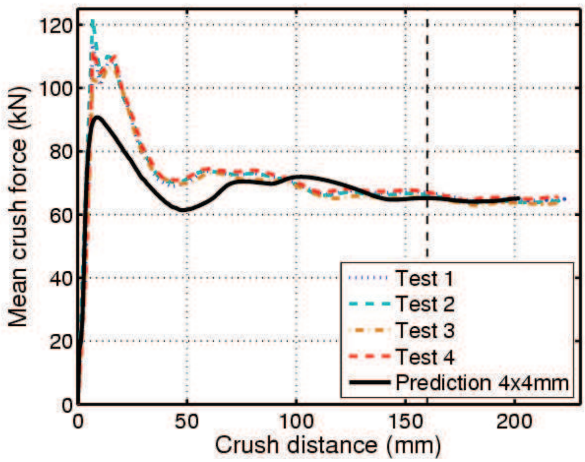

Figure 3: Measured and predicted mean crush forces

Then, the analysis of the effect of the mesh size was performed by remapping forming results on different mesh sizes of 6x6 mm, 8x8 mm and of 10x10 mm for the subsequent simulations. To remap the results from a fine mesh into a new coarser one, the following procedure was required:

1. Knowing the geometry of the die and the reduction of the tube length, a new geometry of the deformed tube is created using Pro Engineer.

2. The new deformed geometry of the tube was meshed with different element sizes using ANSYS.

3. A simulation that remaps the results from the old mesh of the deformed tube to its new mesh was run with the control card *INCLUDE_STAMPED_PART of LS-DYNA. The following variables were mapped:

   - thickness of each element,

- stresses at each integration point,

- equivalent plastic strains at each integration point,

- strains at the inner and outer surfaces of the elements.

PREDICTED CRUSH RESPONSE – WITHOUT REMAPPING

This section provides results based on simulations performed using the same specific mesh size for all the operations from the hydroforming up to the crush event with forming histories. The analysis was performed with mesh sizes of 4x4, 6x6, 8x8 and of 10x10 mm. The results of the predicted mean crush force as function of the crush distance are shown in figure 4. The mean crush forces at a crush distance of 160 mm are given in table 1, which was determined by dividing the energy absorbed at 160 mm by this crush distance.

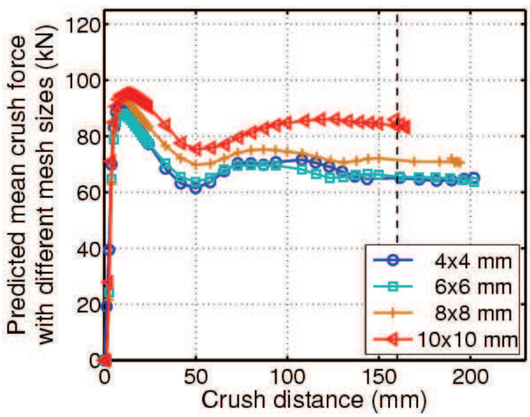

Figure 4: Predicted mean crush forces with different mesh sizes

Compared with the experimental results, the mean crush force for the mesh size of 4x4 mm is 1.8% lower. This shows that using a fine mesh for all simulations and considering forming history allowed adequate prediction of the energy absorption characteristics during axial crush. However, the results also show that using a coarser mesh greatly decreased the accuracy of the predictions. Compared to the measured crush force, the predictions using the mesh size of 10x10 mm overestimated the crush force by 26.1 %.

Table 1: Mean crush forces predicted for simulations without remapping.

Source	Mean of tests	4x4 mm mesh	6x6 mm mesh	8x8 mm mesh	10x10 mm mesh
Mean crush force (kN)	66.4	65.2	65.5	71.5	83.7
Relative error (%)	-	1.8	1.2	7.7	26.1

PREDICTED CRUSH RESPONSE – WITH REMAPPING

Hydroforming simulations were performed with a mesh size of 4x4 mm. The forming history was then remapped to crush simulations with 6x6, 8x8 and 10x10 mm mesh sizes. The predicted results of the mean crush force as function of the crush distance are shown on figure 5 for the different mesh sizes used for the crush simulations.

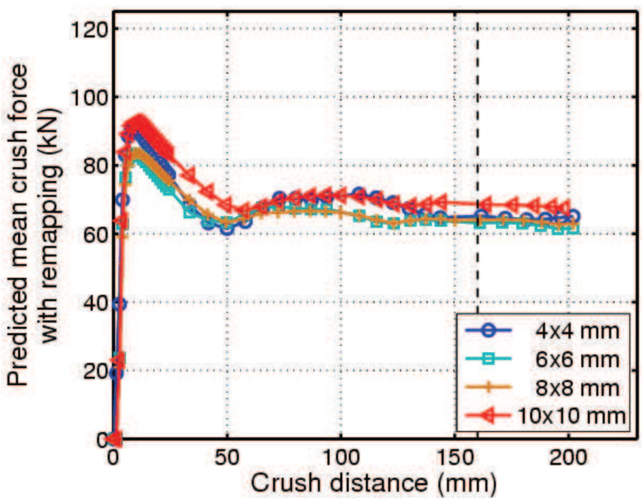

Figure 5: Mean crush forces evaluated during crush simulations with remapped forming results

As shown in figure 5, the predicted mean crush forces are all similar at a crush distance of 200 mm. These solutions are now closer to the measured ones for the 8x8 and 10x10 mm mesh sizes compared with those shown in figure 4. The corresponding mean crush forces evaluated at a crush distance of 160 mm are given in table 2.

Table 2: Mean crush forces predicted for simulations with remapping.

Source	Mean of tests	4x4 mm mesh	6x6 mm mesh	8x8 mm mesh	10x10 mm mesh
Mean crush force (kN)	66.4	65.2	63.1	64.0	68.9
Relative error (%)	-	1.8	4.9	3.6	3.7

As observed, there is an increase of less than 4 % for the predicted mean crush force when the finite element results are remapped from a mesh size of 4x4 mm to a new coarser one of 10x10 mm. From the results previously shown in table 1, the relative error for the mesh size of 10x10 mm is now decreased by 22 % with the remapping technique compared to the use of a larger element size (10x10 mm) for the overall successive simulations beginning with the hydroforming and up to the crush. The results have shown that there is an important advantage to use the LS-DYNA option *INCLUDE_STAMPED_PART when taking into account of forming results in crush simulations. As a result of remapping, the mesh size can be significantly reduced for the crush simulations while maintaining accurate energy absorption predictions.

As the goal of using the remapping technique is to save computational time during the crush simulation, the time that has been required to complete the previous simulations is analyzed in table 3. As observed in table 3, it is useful to use coarser element sizes in order to run faster simulations. All of the crash simulations presented above where performed with a SMP version of LS-DYNA and two Opteron processors of 2.40 GHz.

Table 3: Computational time required to complete crush simulations with remapped forming results.

Mesh size	4x4 mm	6x6 mm	8x8 mm	10x10 mm
Number of elements	7587	3976	2376	1548
Computational time	33 minutes	11 minutes	4 minutes	3 minutes

SUMMARY AND CONCLUSIONS

Two different methods that can be used with LS-DYNA to reduce the computational time required for crush simulations were analyzed. The results showed that under these circumstances, the remapping technique may lead to a lower relative error of the crush force for all the analyzed mesh sizes, compared to predictions in which remapping was not used. It is then preferable to perform the hydroforming simulation with a fine mesh and thereafter remap the finite element results on a coarser one to get more reliable crush characteristics solutions. Also, by performing crush simulations with a coarser mesh, the computational time for the solutions may be significantly reduced compared to crush simulation with finer meshes, while potentially maintaining accurate energy absorption predictions.

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