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THE EFFECT OF FORMING ON THE CRASHWORTHINESS OF VEHICLES WITH HYDROFORMED FRAME SIDERAILS

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ABSTRACT

This paper describes the use of forming simulation output data from a hydroformed frame siderail as initial material properties for crash simulation of the component. The hydroforming simulation model is described and correlated to test measurements. Methods developed to transfer data between forming and crashworthiness analyses are presented and the limitations of the existing systems identified. The frame siderail was subjected to a representative crash load; LS-DYNA was used for both forming and crash simulations. The effect of thickness, work hardening and residual stresses on the crashworthiness results is quantified; crash response is seen to be significantly affected when the effects of forming are included.

INTRODUCTION

BACKGROUND

Metal forming processes result in a number of changes in the material properties of a formed component. The initial blank material is subjected to large deformation during forming which results in changes in the thickness and yield point of the material. Another result of the forming process is the residual stress distributed across the component. These material properties are important inputs to computer-aided engineering analyses of component response, for example crash or durability models. A change in these properties could have a significant effect on the results of such analyses and could lead to a sub-optimal design. By using the output data from forming simulation as the input to other types of modeling it is possible to investigate the significance of these changes to the integrity of the component.

OBJECTIVES

The two objectives for this work were:

- To establish a method to take forming analysis data into the crashworthiness model (including thickness, work hardening and residual stresses)
- To determine the relative importance of each parameter.

Other work (1, 2) has suggested that thickness changes and work hardening during forming can alter the predicted structural performance in crash or fatigue. The current work was intended to quantify these effects for a hydroformed siderail and gain understanding to allow for wider implementation.

FORMING ANALYSIS

METHOD

Forming of the siderail was modelled in LS-DYNA (3). The sequence of forming operations is shown in Figure 1. From an initial tube with a diameter to thickness ratio of 40, the tube undergoes a bend operation, followed by a mechanical preform before the hydroforming stage. Internal pressure reaches a maximum of around 100 MPa; axial force is applied at both ends of the tube to feed material during the pressurisation cycle. The final cross-section across the majority of the siderail is approximately rectangular with a typical expansion of around 9%. Initial variations in the tube properties from the roll forming operation and any effect of the weld were neglected.

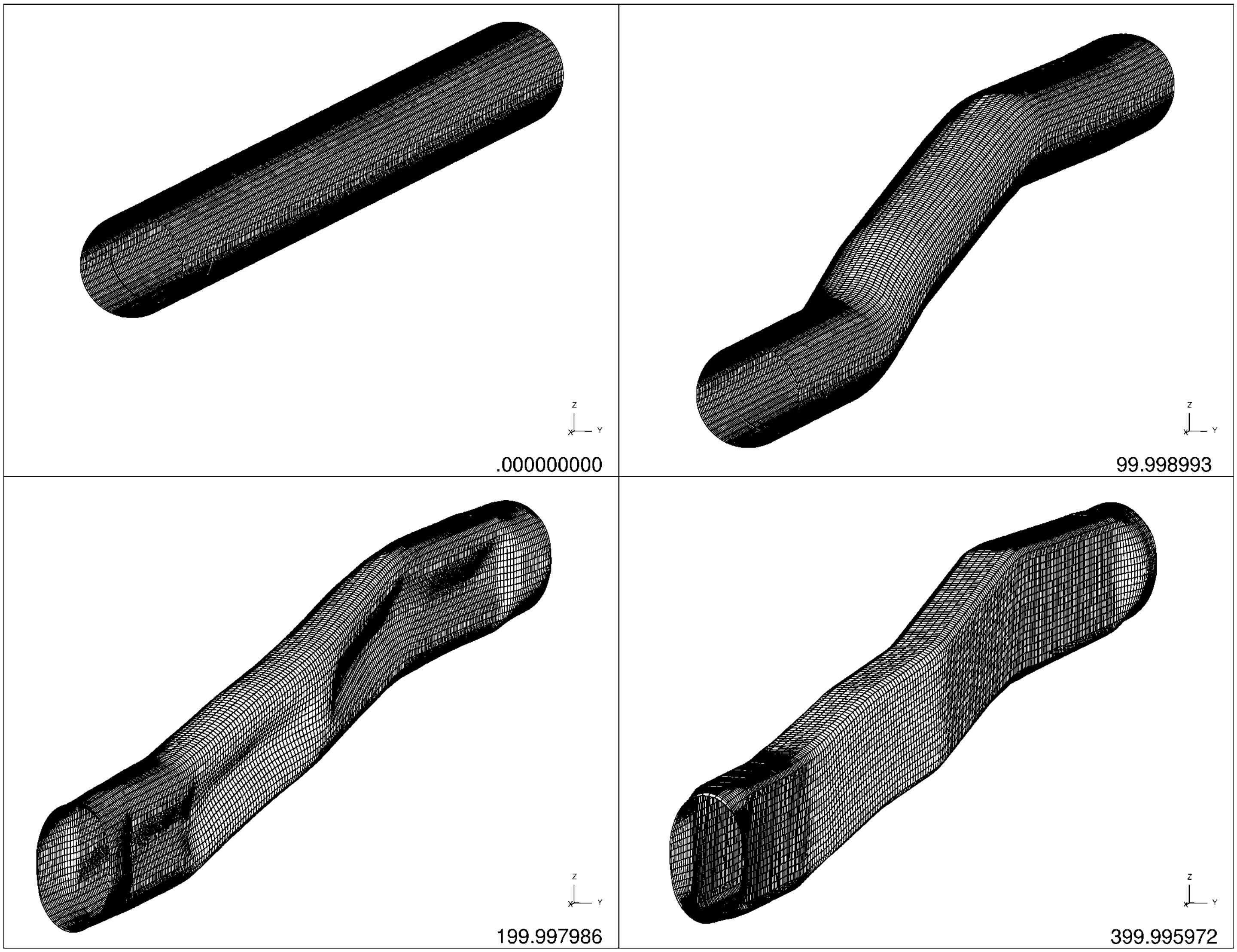

Figure 1. Sequence of Forming Operations (initial undeformed tube, press bend, press bend and form, hydroform)

FORMING ANALYSIS RESULTS

Figure 2 shows the results of the hydroforming process, indicating thickness strain, plastic strain and residual Von Mises stresses (kN/mm^2, before and after springback); LS-NIKE3D (4) was used for the springback simulation.

It was notable that the overall change in thickness was not dramatic with thinning mostly restricted to the outside of the bends; axial end feel causes thickening concentrated at the rail ends. However, a large amount of material experienced considerable work hardening, as indicated by the plastic strain data, with many areas showing more than 10% strain. The Von Mises stresses at the end of forming are high (the forming simulation ends with internal pressure at its maximum value). These fall significantly following springback with negligible stress in most of the siderail except for some regions, such as on the inside of bends, where stresses remain locked in (N.B. different scales are used for the two stress plots).

VALIDATION OF FORMING ANALYSIS

Before proceeding with the investigation of forming effects on crash, it was important to confirm that the forming analysis model was suitably accurate. In order to validate the forming model, 24 tensile test coupons were cut longitudinally from a hydroformed part, at the locations shown in Figure 3. The thickness and yield stress of each specimen were measured and compared to the corresponding forming simulation results.

Table 1 compares the thickness and yield stress values for each of the 24 locations measured. The predicted yield stress is derived from the plastic strain predicted by the forming model, assuming reloading as shown in Figure 4. Rather than follow the specified stress against strain relationship from zero plastic strain, the element instead follows a load path to reach the yield surface at a higher value of stress. In this way, an element of the material in the forming analysis initially yields at 230MPa and is strained to, say, 20%; on reloading, this element will now yield at 400MPa.

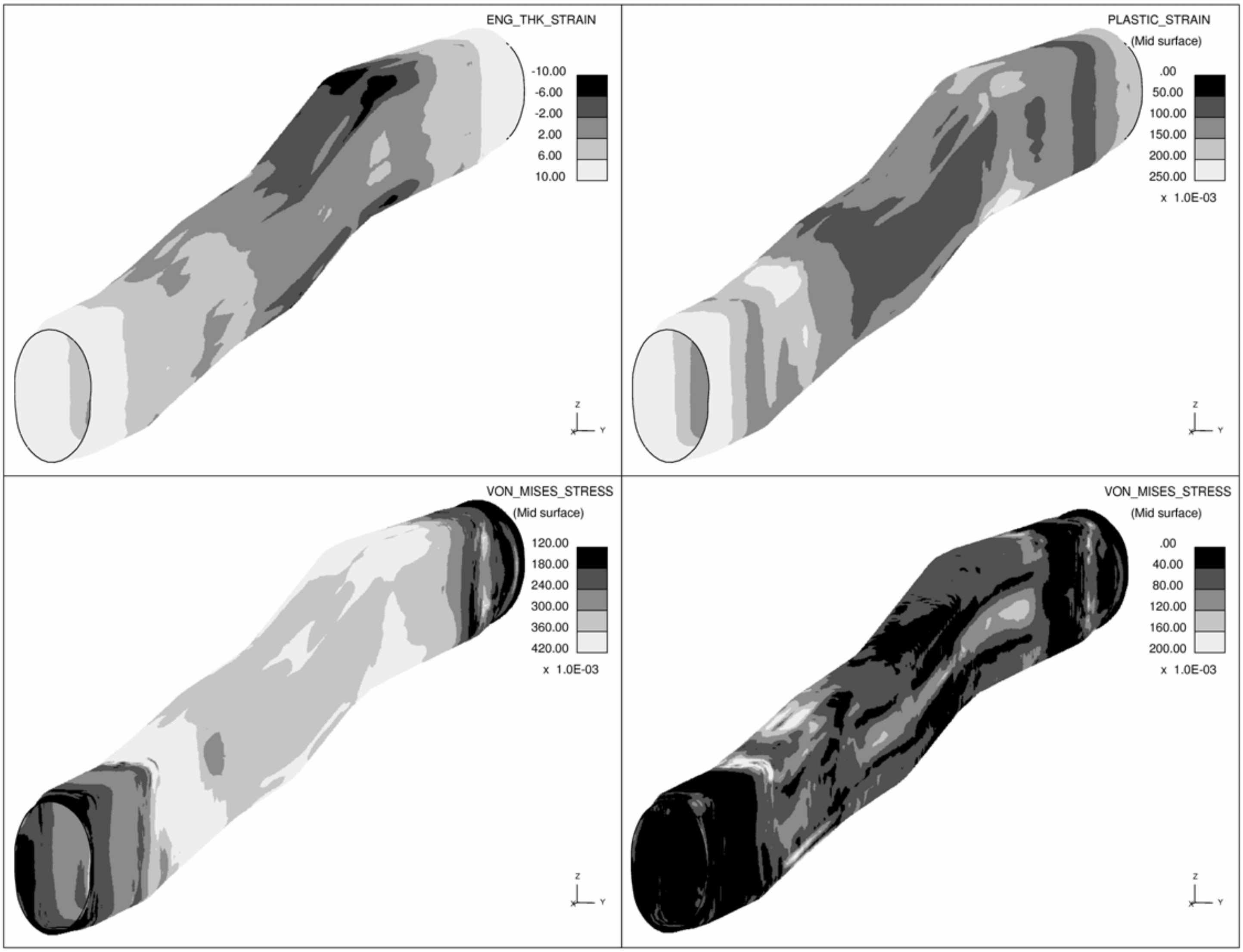

Figure 2. Results of Forming Analysis (thickness strain, plastic strain, residual stress before and after springback)

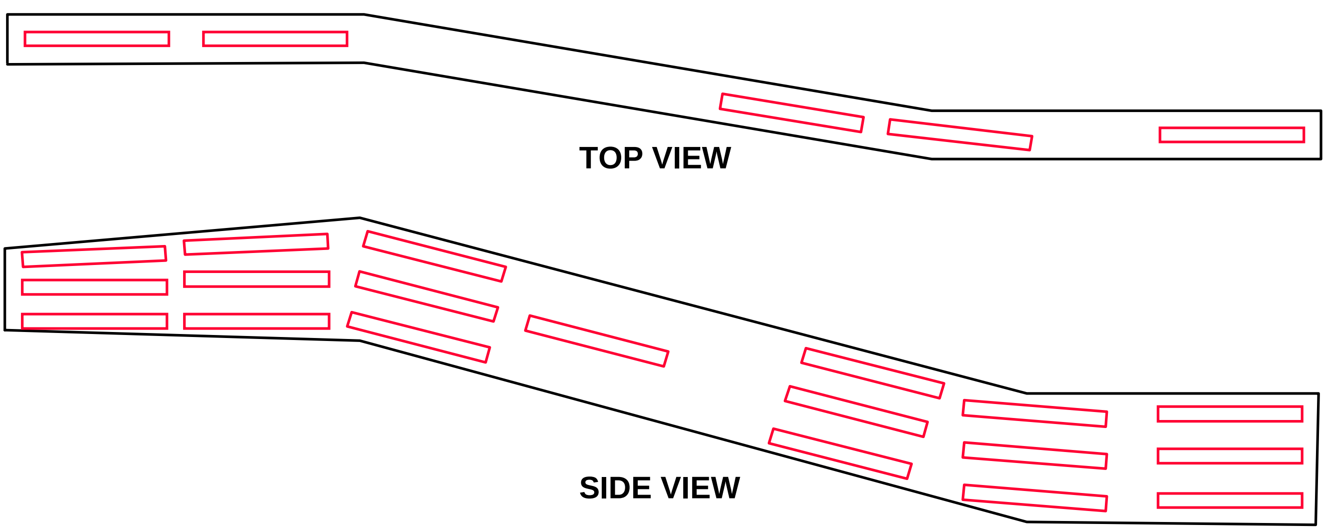

Figure 3. Location of Test Samples cut from Hydfroformed Siderail

The average thickness change measured from the tensile test specimens was –5.1% compared with the forming simulation prediction of –3.4%. Most of the simulation values are within 2% of the measurements and in only two of the 24 locations did thickness values differ by more than 4%. Fourteen (58%) of the predicted values of yield stress differ by 20MPa or less from the measured data; differences greater than 50MPa occur in just four of the samples, generally where the sample had to be flattened before measurement.

Table 1. Properties after Hydroforming

Thickness Change		Yield Stress [MPa]	
Measured	Predicted	Measured	Predicted
-3.3%	-1.1%	326	317
-1.3%	0.2%	364	302
-1.3%	-1.6%	287	317
-7.6%	-5.5%	378	366
-1.8%	-1.1%	345	296
-9.6%	-6.7%	418	373
-7.8%	-9.0%	380	394
-2.5%	-0.6%	321	306
-7.6%	-6.9%	390	390
-2.5%	-0.1%	331	283
-4.5%	-3.9%	364	368
-0.5%	1.0%	352	289
-1.3%	-4.3%	342	355
-15.4%	-0.8%	451	357
-5.8%	-3.0%	377	324
-14.6%	-10.7%	461	413
-5.8%	-5.5%	356	376
-1.3%	-1.8%	342	338
-4.5%	-5.1%	357	373
-1.3%	-1.2%	323	327
-6.3%	-5.8%	368	364
-6.3%	-5.1%	374	366
-4.5%	1.0%	421	371
-5.8%	-4.7%	383	371

These results lead us to believe that the forming model is reasonably accurate and that the forming data from the simulation is suitable for use in the effects of forming study. The measurement comparisons also support the use of plastic strain to establish the yield stress in the formed material as shown in Figure 4.

It can be observed that in the few measurements where thickness has been particularly underestimated in the model there is an accompanying under prediction of yield stress. One possible explanation for this is that friction effects may have been locally underestimated in the simulation, perhaps due to the fact that process parameters such as lubrication are more complex than can be represented by the simple Coulomb Law method used in the model.

DATA TRANSFER METHOD

A variety of methods was explored to transfer the important data from the forming analysis into the crashworthiness model. The key parameters to be taken forward were the thickness changes at each node, and the plastic strain value and stress tensor for each integration point at each element. Data was taken forward node by node and integration point by integration point, rather than by selectively re-partitioning the crash model according to a range of averaged material properties. While this approach leads to an increase in the size of the crash input model and may

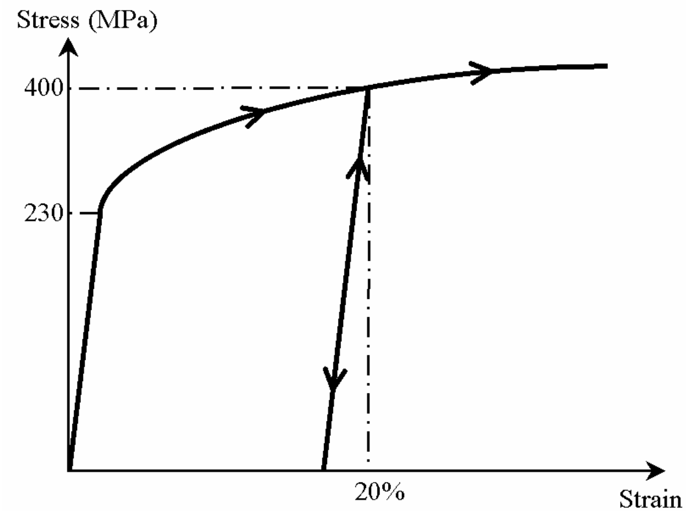

Figure 4. Stress versus Strain Relationship

increase its initialisation time, this was not seen to outweigh the extra work and the approximations introduced defining zones manually.

Use of thickness data and initial stress tensors in the crash model is straightforward; these simply become the starting points for each element. By specifying an initial plastic strain value we can effectively change the yield stress element by element to introduce the effect of work hardening (i.e. the same method used for predicting yield stress from plastic strain in the analysis validation described previously). Isotropic hardening was assumed; the difference in the results due to the Bauschinger effect has not been examined.

The same material model (*MAT_PIECEWISE_LINEAR_PLASTICITY) was used in both forming and crash analyses; strain rate effects and material failure were ignored.

The most direct approach to transfer the effects of forming is simply to couple the two models, analysing both the forming process and crash event in one continuous analysis (or almost continuously, using the full deck restart facility). This is clearly limited in its usefulness but ensures that every possible parameter of interest is transferred from one phase to the next. Indeed, other parameters that may or may not be wanted are transferred including instantaneous nodal velocities, which can in fact have an effect on the crash results. Values that may be useful to monitor the state of the material, such as internal energy and strain tensor, can also be carried straight through.

For greater flexibility, not only when moving from one LS-DYNA model to another but also to take data to other types of analysis, a more general method was needed to take data from the forming analysis for initialisation of the next analysis. LS-DYNA creates a wide range of ASCII and binary output files that can be used directly or via post-processor options (in e.g. *Oasys* D3PLOT). It should be noted that some output is in local rather than global co-ordinates. But the most useful feature of LS-

DYNA was its ability to create a new input file at the end of the forming analysis (default name *dynain*) that contains all the required data (plus element connectivity and nodal co-ordinates) for a specified part of the forming model. This approach was used throughout this study. A simple Fortran program was written to allow sections of the *dynain* file to be selectively omitted.

The present study has not addressed mapping of the element mesh from the forming model to the crash model; i.e. the same finite element mesh has been used for both forming and crash. No adaptive re-meshing was used in the forming analysis. Also, the forming model was not re-oriented for the crash analysis, nor was it re-connected to other deformable components. This phase of the study was primarily intended to establish the importance of and any practical limitations in taking forming parameters across; hence, the development of a general-purpose mesh mapping and re-orientation tool was omitted.

This method was tested on a simple model of the forming and crushing of a circular tube. Successful transfer of the different parameters was confirmed.

SIDERAIL CRASH ANALYSIS

CRASH MODEL

To create a model to evaluate the crash behaviour of the formed siderail, certain features of the formed rail were modified. The round ends were trimmed and simple constraints were added to limit lateral collapse, representing the effects of cross members and other components in the actual vehicle. The far end of the rail (2.5m in length) was held rigidly. A number of nodes were moved to represent the crush initiators in the tapered front horn of the rail (no elements were added or deleted). The effect of the forming process to create these features was not included, however. The crash load was simulated by a 500kg rigid plate with an initial velocity of 10m/s. The collapse of the rail, mode of deformation, amount of stroke, reaction forces and energy absorption were then analysed and compared for the following cases:

1) standard analysis (i.e. nominal thickness and no initialisation of stress and strain)

2) thickness only initialised

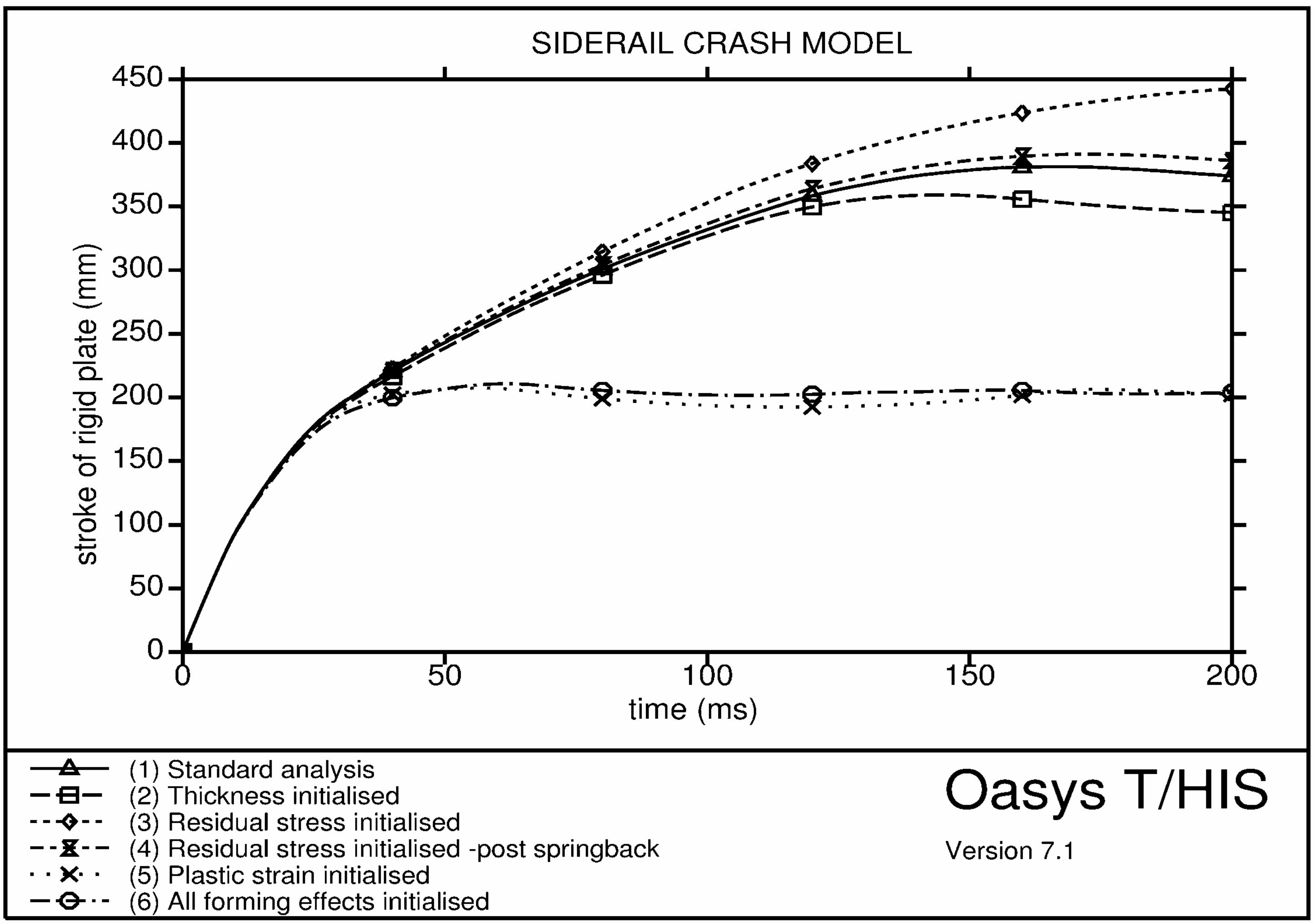

Figure 5. Stroke of Rigid Plate showing effects of Forming Parameters compared with Results of Standard Analysis

3) residual stresses initialised

4) as (3) but after stress alleviation by springback analysis (N.B. the small changes in geometry due to springback were neglected)

5) plastic strain initialised, to represent the effect of work hardening

6) all forming effects initialised (N.B. stress values used were pre-springback).

RESULTS

The analyses revealed a significant difference in the stroke of the rigid plate for the six cases. Figure 5 shows the displacement, or stroke, of the plate against time. The standard analysis (1) had a maximum stroke of 380mm; case (2) thickness, (3) residual stress and (4) residual stress post-springback show small variations around this value. Thickness changes in fact resulted in a stiffer response showing that the nett effect of the forming process was to thicken the siderail, at least in key areas deformed in crash. Comparing (3) and (4) with (1) shows that the pattern of residual stress changes tends to weaken the rail but that after springback these effects almost disappear.

However, the most obvious change results from case (5), the initialisation of plastic strain tending to work harden the rail to the extent that the stroke of the plate is reduced to 210mm, some 45% less than the standard analysis. Case (6) with all forming effects included is almost identical to case (5); the rail appears marginally weaker, probably due to the residual stresses (pre-springback) outweighing thickening effects. Clearly, work hardening is dominating all other effects.

Figure 6 compares the final deformed shape in case (1) above with case (6) below. It is clear that different modes of collapse have taken place. It appears that work hardening discourages the relatively weak bending failure in the rearward part of the rail that occurs in case (1), and instead the more energy efficient mode of front horn crushing dominates in case (6). This is confirmed from an examination of the internal energy absorbed in the front section of rail in the two cases. In the standard analysis only 63% of the impact energy is absorbed in front end crush compared with 78% in the work hardened case.

SENSITIVITY ANALYSES

In order to confirm that the results were not unduly sensitive to the conditions set for this study a number of variations were analysed. The effect of the crush initiators, lateral constraints and initial velocity of the rigid plate was examined. The trend of the results as presented above was unchanged.

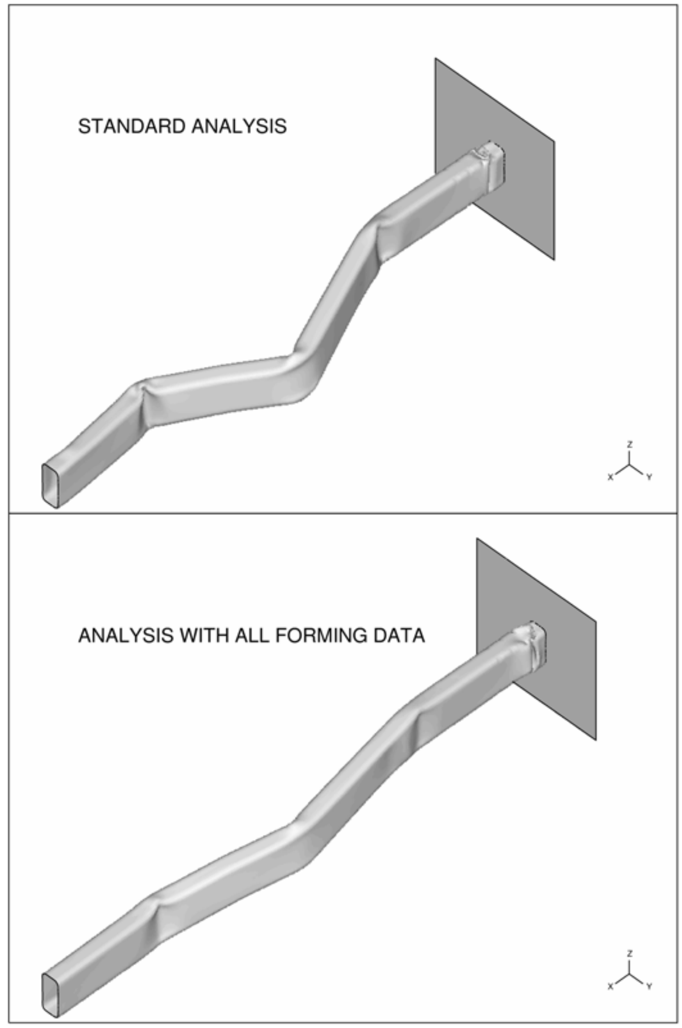

Figure 6. Deformed Shapes of Siderail, Standard Analysis (case 1) above, All Forming Effects (case 6) below

FURTHER STUDIES

In order to gain better understanding of why the mode of collapse changed with work hardening a series of extra analyses were set up based on case (6). Eight models were run with a modified stress vs. strain relationship for either the front part of the rail (which absorbs energy chiefly by crushing) or the rear part (which absorbs energy chiefly by bending) to give a yield stress independent of plastic strain in forming. Four values of yield stress ranging from 150MPa to 450MPa were examined for each part of the rail. The reactions at the far end were compared.

Figure 7 shows a graph of peak reaction force against yield for the two types of collapse, mostly crush and mostly bending. It shows that above a certain value of yield stress (around 370MPa in this case, equivalent to a plastic strain of ~15%) there is a transition from a tendency to fail in bending to a tendency to fail in crush. As load builds up in the siderail, the mode of collapse will be that with the lowest load for the given value of yield stress.

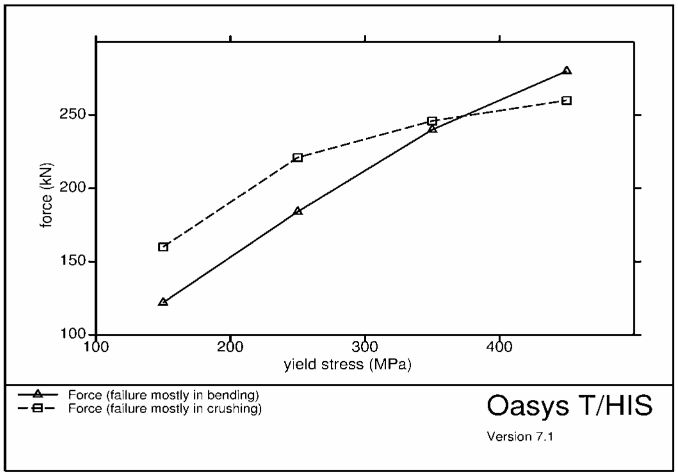

Figure 7. Relationship between Force and Yield Stress for Different Collapse Modes

Figure 2 shows that a considerable amount of the rail reaches 10% strain with many key areas seeing more than 15%. This explains why introducing the effects of the forming process, and in particular the change in yield stress due to work hardening, had such a significant effect on the crash response of the frame siderail. It would appear that these effects must be included to predict correctly the mode of failure for this and similar components.

DISCUSSION

The analysis work carried out in this study has identified a case of a hydroformed siderail in which the crash response shows a strong sensitivity to the effects of work hardening during forming. The observed difference could well lead to a quite different prediction of the crash behaviour of the entire vehicle, especially when it is considered that up to 70% of impact energy is absorbed by the chassis rail (1). This is clearly important as vehicle developers aim to reduce the number of physical prototypes and rely more and more heavily on computer-aided engineering to predict vehicle performance.

The measurements of thickness and yield stress indicated that the forming analysis model was reasonably accurate. They also supported the assumptions made on how the forming process affects the formed component, particularly with respect to the relationship between plastic strain and yield stress. Interestingly, it has been found by others (5) that the mode of forming can affect the amount of hardening. Biaxial prestrain was seen to cause an even greater increase in yield stress than would be predicted by the approach described above, due to what was termed redundant strain in the material. This effect has not been considered in the study reported here, however, but merits further investigation.

Further work is needed to extend this study to the more general case of a full vehicle model but it seems evident that these factors should not be neglected when attempting to predict crashworthiness. It could be that hydroformed rails are particularly prone to this effect as the forming process causes an amount of both thickening and thinning but considerable amounts of plastic strain and hence work hardening. A stamped "C" section frame might show more exaggerated thinning and less widespread work hardening and thus quite different overall trends.

Work is planned to simplify the analysis procedure with modification to the LS-DYNA pre-processor; this needs to include a mesh mapping capability. A number of other analysis parameters, including strain rate effects, will also need further investigation.

Given the importance of forming changes on crash response, it would be prudent to examine the effect on other aspects of vehicle performance such as durability.

CONCLUSIONS

This study has established a method to transfer data from the forming analysis to the crashworthiness analysis (both using LS-DYNA), allowing thickness, residual stress and plastic strain data selectively or in combination to be used to initialise the crash model. The relative effect of each of these forming parameters has been examined and the importance of, in particular, work hardening on the crash response of the hydroformed siderail has been identified. A significant change in energy absorption, peak force and stroke of the siderail was predicted, indicating a far stiffer response in the formed rail than would be expected based on the nominal material properties. Therefore, forming effects should be accounted for in vehicle crashworthiness predictions.

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