INTEGRATED ANALYSIS OF FORMING AND CRASHWORTHINESS OF HIGH STRENGTH ALUMINIUM BUMPERS USING LS-DYNA

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Abstract

The front and rear bumper beams are important parts of the overall safety system of modern cars. Due to aluminium's high strength to weight ratio, bumper beams made of extruded aluminium profiles have become an attractive contribution to the car manufacturers' constant strive for reducing the weight of their cars.

In order to meet the various demands with respect to weight, strength, functionality, packaging , etc., a significant degree of complex forming after extrusion is normally required. As a leading supplier of high strength aluminium bumpers, Hydro Automotive Structures have for several year been using advanced FE tools in their

product and process development. However, due to the close link between crash performance and geometrical shape of the bumper, the need for a tighter integration between process and product simulations has been realised.

The present paper shows examples of how such integrated analyses are carried out in an industrial context as well as some results indicating the clear benefits of such an approach.

Introduction

The use of aluminium extrusions in cars has shown a steadily increasing trend during the last decades. This is a trend that is expected to continue in the years to come. The main advantage of aluminium over other materials for structural use, is the high strength to weight ratio. Furthermore, the extrusion process itself offers an excellent way to put functionality into the products, e.g. to put material where it is needed.

Examples of typical application areas for aluminium extrusions are:

- bumper reinforcement beams
- seat structures
- body frames (sub-frames or complete space frames)
- roof rails
- roof reinforcement bars for convertibles (soft tops)

In order to add functionality, meet geometrical constraints, optimise rigidity, etc., a substantial degree of reforming of the initially straight extrusions is normally required. This reforming may include global shaping (bending, twisting) as well as more local reforming of embossments, imprints, etc.

Traditionally, product and process development have been carried out as separate and sequential activities. Such an approach may have several disadvantages:

- time consuming
- insufficient communication between functional departments (e.g. feedback from process evaluations back into the product development activities)
- risk of developing products with poor manufacturability
- difficult to identify 'risky' projects early enough.

In the present paper an example will be shown of how integrated product performance and process simulations can help overcoming many of these disadvantages.

Before proceeding to the example, some more general issues related to both forming and product performance analyses of bumpers will be addressed.

Extrusion forming

Upon designing a forming process for an aluminium extrusion, the following aspects should be given due consideration.

- cross-sectional stability/distortions
- elastic spring back
- robustness (i.e. insensitivity to inherent process and geometry variations)
- cycle times
- costs of tooling and process

When subjecting an extrusion to bending, the cross-sectional segments located at the tension side will generally move towards the neutral axis. This sagging behaviour is largely controlled by the wall thickness, flange width and level of tensile stresses. In the case of open sections, sagging can be avoided by introducing appropriate tool support. For closed (hollow) sections, the application of internal support tools (mandrels) is generally complicated or undesired from a productivity point of view. As far as possible, one should therefore attempt to control cross-sectional distortions by optimising both process and geometry.

As far as elastic spring back is concerned, this is an inherent feature in all kinds of metal forming, However, due to a lower Young's modulus, the amount of elastic springback is larger for aluminium than e.g. for steel. As long as the spring back is constant and reliable estimates can be found, an appropriate spring back compensation is easily achieved by modification of the tool geometry. However, most of the parameters controlling spring back (e.g. flow stress, cross-sectional dimensions and friction) will typically vary, thus causing the spring back also to vary. The process therefore has to be designed so as to minimise the influence of input parameter variations, i.e. make the process as robust as possible.

The design and optimisation of a forming process for extrusions can be a complicated and time consuming undertaking. The use of simulations is therefore of vital importance. As the main reasons for doing process simulations can be mentioned:

- process design (i.e. determine required forming operations to achieve the desired shape)
- process and geometry optimisation
- demonstration of process capability (according to e.g. QS9000)
- reduce lead times

Forming an extrusion into the desired shape may require several forming operations, e.g. bending, stamping, calibration, trimming, hole punching , etc. The sequence in which these operations are carried out is by no means arbitrary. For instance, a trimming operation coming after a global bending operation will have a significantly different effect in terms of stress re-distributions, etc. than the same operation being done prior to the bending. In this respect, performing process simulations will help determining the most appropriate combination of forming operations.

Once the forming route is determined, each forming operation has to be optimised. Traditionally the major part of the required optimisation has been carried out as a part of the running in of the corresponding tooling in the press shop. Doing process optimisation in this way is both inefficient and costly, and being able to move the process optimisation from the press shop to the computer has obviously a great cost and time saving potential.

In addition to making the process optimisation more efficient, also the time used for running in of tooling can be reduced significantly. This work is often based on a trial-and-error approach and can be very time consuming. Any activity that can reduce the number of iterations in the tool trimming lines has a corresponding effect on the total lead time for the product.

The term *process capability* is normally related to the degree to which the output from a process is within the specifications. A relatively new trend in the automotive industry is that the customers at the pre-contract stage not only require a proper demonstration of the product performance, but also of the process capability.

Unless historical data from similar processes can be provided, process simulations may be the only way in which the required process capability can be demonstrated.

Product development of bumper systems

A product development process is typically subject to a lot of requirements and constraints. First and foremost, the product has to meet a set of functional requirements. At the same time particular constraints like price, weight, appearance, production time, etc. cannot be violated.

For a bumper beam, the main requirements with respect to functionality are related to energy absorption under impact loads (i.e. a crash situation), at low speeds (< 16 km/h) as well as high speeds. Another function is to bridge the car's longitudinals and thus increase the stiffness of the car structure giving improved car performance with respect to handling characteristics, NVH (Noise, Vibrations and Harshness), etc.

The performance of bumper beams are regulated by a number of both national and international standards. In brief, the requirements with respect to crash performance can be divided into three categories:

1. Law requirements

Depend on where the car is sold but generally these requirements are based on certain minimum performances in barrier and pendulum tests with velocities ranging from 2.5-8 km/h.

2. Insurance classification

These are also depending on where the car is sold. In Europe the AZT/Danner/Thatcham test is widely used for classification. A description of this test procedure is given below in the section "Crash simulations"

3. Internal requirements

In some cases the car manufacturer adds extra requirements, for instance no plastic deformation of the bumper system up to a certain velocity.

Like the case for process development, FE simulations have become an indispensable tool in the product development stage.

Integrated product and process development

For a product to be formed, the forming processes are closely linked to the product design, and since the forming processes have a very strong influence on the total production costs, it is rather obvious that some kind of forming process evaluation should be an integral part of any product development activity. Small details in the product with often negligible effect on the overall functionality, e.g. unnecessary tight tolerances, may adversely affect the complexity of the forming process and thus add considerably to the product cost. The costs of introducing design modifications often increase exponentially with time, thus underlining the need for performing process evaluations as early as possible at the product development stage. Performing process simulations should therefore be an as natural part of product development as e.g. product performance simulations (crash simulations, etc.).

In the following, an example of how process simulations more directly can be integrated in the product development activity will be given. The product involved is a rear bumper beam for a small sized car from a major European carmaker. A CAD model of the product is shown in Figure 1. The bumper is of a monobeam type, i.e. there will be no additional energy absorbers (crash boxes) between the beam and the car's longitutinals

Since the CAD engineers normally have limited experience in evaluating how the extrusion will deform during a future forming process, the traditional and straight forward way of establishing the CAD model of such a beam, is to 'sweep' the relevant cross-sections along the contours defining the global shape of the bumper

The process chosen for this bumper is based on a conventional stretch bending process as shown in Figure 2. The end regions are forced to remain horizontal throughout the process. Due to this constraint on the ends, the process is characterised by a global shear mode of deformation rather than a bending mode. The shear mode will make the side webs very prone to geometrical instabilities.

The main process parameter for the process above, is the horizontal motion Δ of the clamps. This feeding will determine the overall stretch in the extrusion as well as the conditions controlling the instability phenomena of the side webs.

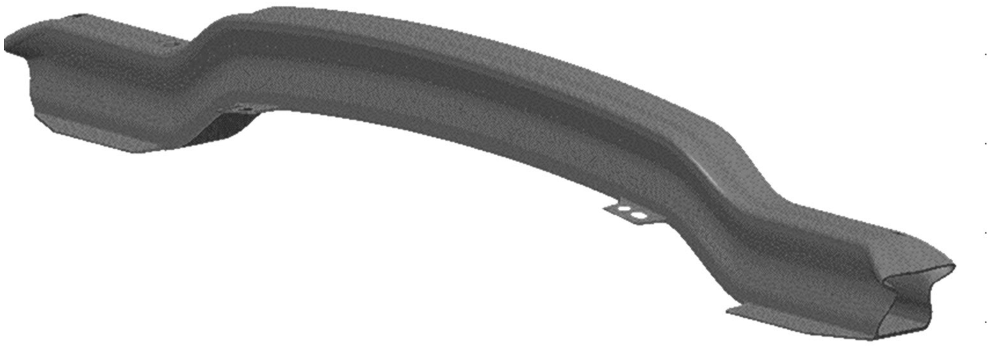

Figure 1: CAD model of the investigated bumper beam.

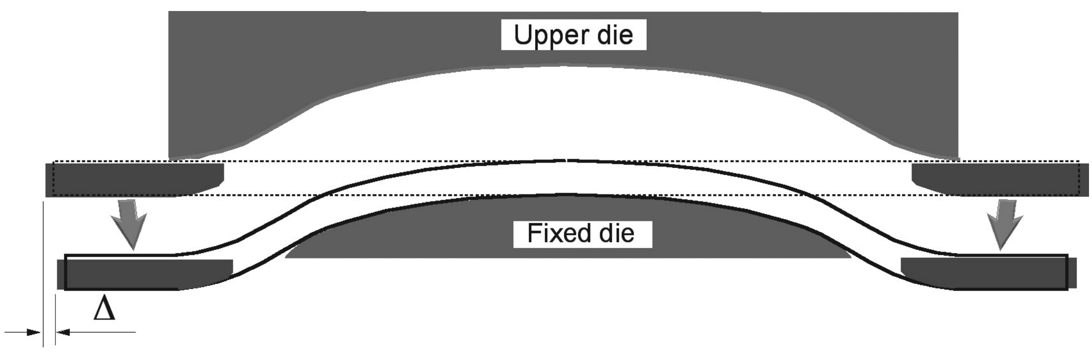

Figure 2: Schematic view of the forming process.

Simulation of the forming process

In order to investigate the response of the bumper beam during forming, the forming process was simulated using LS-DYNA. The FE model is shown in Figure 3 at various stages of the process. Due to the prevailing symmetry, only one half of the product needs to be modelled. The tooling is modelled as rigid surfaces representing surfaces with die – work piece interactions. The extrusion itself is modelled by 6017 shell elements (Belytschko-Tsay). An isotropic von Mises material (*MAT_PIECEWISE_LINEAR_PLASTICITY) with no strain rate effects is applied.

The forming process takes place in two steps; one clamping step and one bending step. The clamping is achieved by moving the upper clamp die towards the lower clamp die. When the section height is reduced to the height defined by the mandrel, a row of elements in the upper and lower flange of the extrusion are switched to rigid material and constrained to the mandrel. The elements undergoing the deformable to rigid switch correspond to the serrated grippers being an integral part of the upper and lower clamp dies in the real tooling. The bending step is accomplished by a pure translation of the clamping assembly (clamping dies and mandrel) to the final position as defined by the product shape.

The process was simulated for three different amounts of horizontal feeding, D :

Case I : After the clamping step, a prescribed translation in the vertical direction is applied to the clamp dies. The horizontal translation is locked, i.e. $\Delta = 0$. The resulting geometry of this simulation is shown in Figure 4 a). A characteristic feature is the formation of a swage in the *swan's neck* region. As described earlier, this feature is attributable to the shear mode of deformation giving compressive stresses acting in an approx. 45 degrees direction in the side walls.

Case II : The same process as in Case I except for a prescribed horizontal outward motion of the clamp dies. The horizontal motion of 15 mm is applied proportionally to the vertical motion and will result in an additional stretch of the extrusion. The final geometry obtained for this case is shown in Figure 4 b). As can be seen, no swage has been formed and the inverted shape of the side walls prevails along the whole length of the bumper beam.

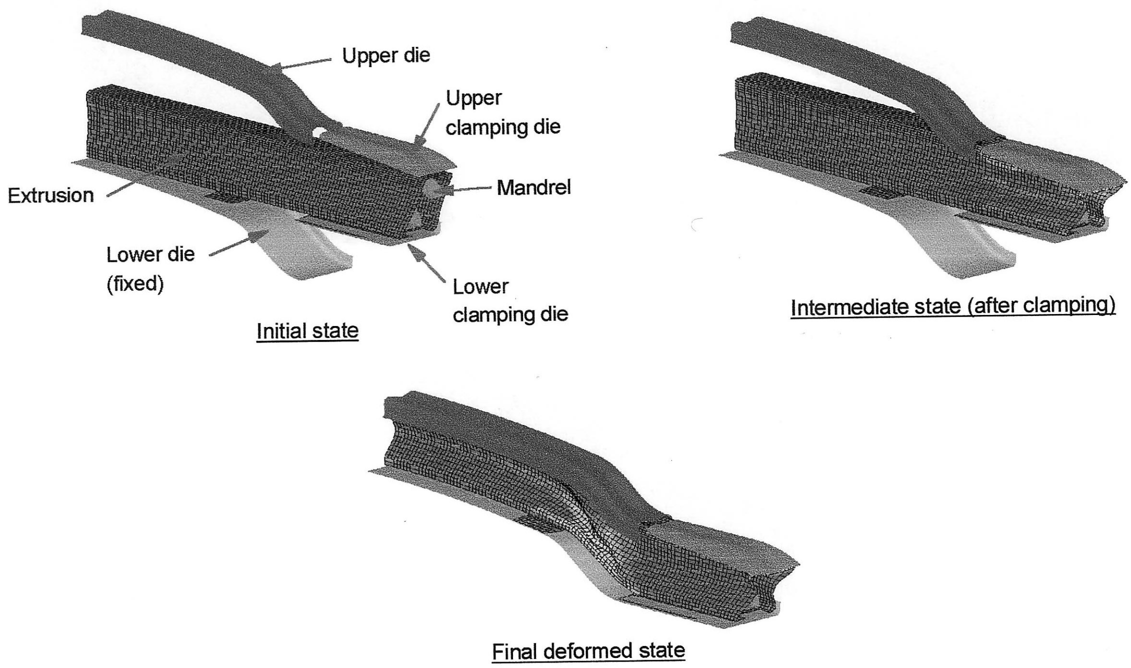

Figure 3: The FE model shown at three different stages.

Case III : In this case, the stretch is reduced by prescribing a horizontal clamp die motion of 15 mm directed towards the centre. The horizontal motion is applied proportionally to the vertical motion but does not start before the latter is half way to its final position. The resulting geometry is shown in Figure 4 c).

Apart from the differences in buckling behaviour, the most significant difference between the three cases is the height of the sections in the region of the swan's neck. As will be discussed later, this dimension is of importance when it comes to crash performance since it directly influences the available working distance for the barrier. Figure 5 shows a section through the swan's neck for the various cases investigated. The cross-section corresponding to the 'nominal' beam geometry (i.e. CAD model) is also shown. Whereas the nominal height is 66 mm, the corres-ponding height is 57 mm for Case I, 54 mm for Case II and 63.5 mm for Case III.

The investigated bumper beam is being manufactured with a forming process corresponding to the one simulated in Case I. The measured section height on the real bumpers is approximately 60 mm, i.e. 3 mm more than the predicted dimension. The observed deviation is in accordance with previous experience. The material in aluminium extrusions is normally very anisotropic with r-values in the longitudinal direction typically well below 0.5. It is therefore not unexpected that by using an isotropic von Mises material description, the global (lateral) contraction will be overpredicted.

Figure 6 shows a comparison between the simulated final geometry (Case I) and the geometry of the real product. Except for the slight discrepancy in section heights in the swan's neck region, the general agreement is very good.

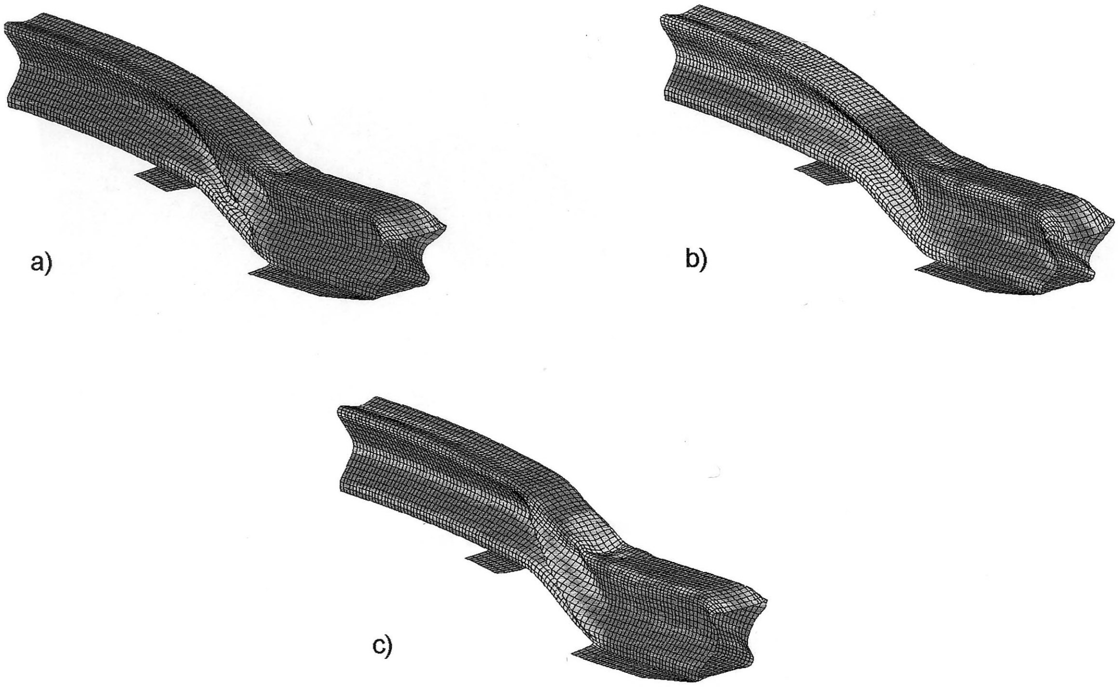

Figure 4: Deformed mesh (i.e. final geometry) for the three process alternatives investigated.

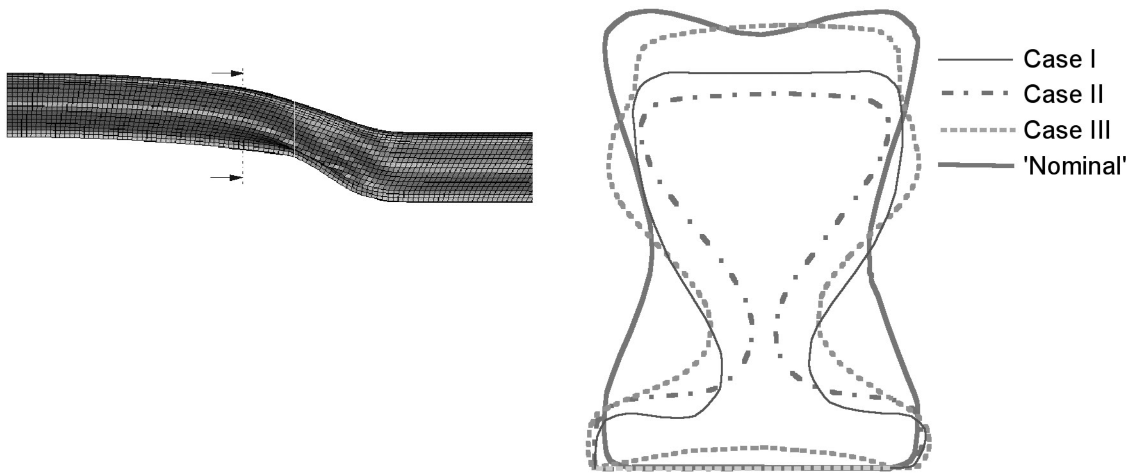

Figure 5: Sections through the bumpers in the region of the swan's neck.

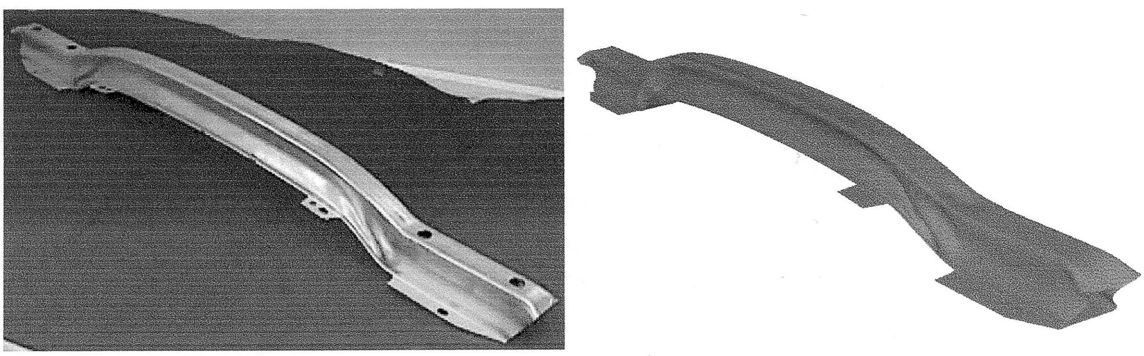

Figure 6: Comparison between real product and simulated geometry.

Crash simulations

Above it has clearly been demonstrated that the forming process may have a significant effect on the final geometry of the product. In order to evaluate whether there are any similar effects on the product performance, crash analyses for each of the three cases above were carried out.

As mentioned before, bumpers will normally be subjected to a number of different tests and crash simulations. In the present work, we will restrict the attention to the so-called AZT test. The general set-up for this test is shown schematically in Figure 7.

For a front test the car crashes into a clamped barrier with a velocity, vc=16 km/h. The overlap between the car and the barrier is 40% of the car's width.

For the rear test the overlap is still 40% of the car width but instead of crashing the car into the barrier, it is in this case the barrier that will be crashed into the car with a velocity, v_r=16 km/h. The car will initially be at rest, but since the brakes are off, the car will normally start rolling as a result of the impact.

As the beam under consideration in the present work is a rear bumper, the latter type of test has been simulated. The applied FE-model is shown in Figure 8.

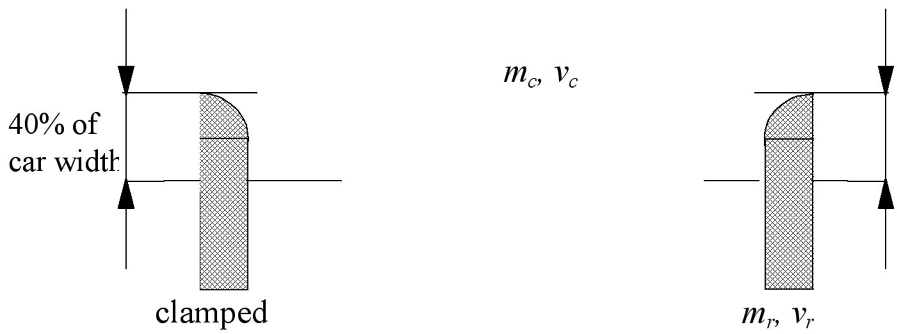

Figure 7: General set-up for the AZT 40% offset crash test.

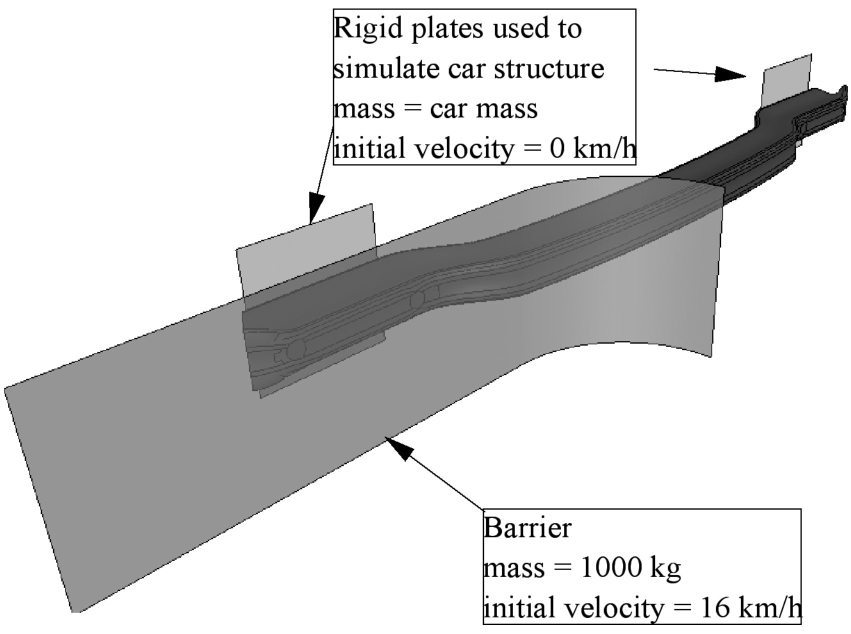

Figure 8: FE-model for crash simulations

The deformed mesh from the forming simulations was imported into a commercial mesh generator (Hypermesh), where the required mirroring, definition of boundary conditions and barrier geometry, etc. were accomplished.

In crash analyses, in particular those of whole cars or systems, an element size of about 5 mm is regarded as a minimum from a computational cost point of view. In the present work, the models used for forming simulation had element dimensions down to 2.5 mm and a remeshing should in principle have been done. Most mesh generators have effective ways to do this remeshing in an automatic manner and can be accomplished without any significant loss of time. Due to the relatively small models involved, the crash analyses in this work were based on the original models from the process simulations without any modifications of the mesh.

The energy absorption capability of a bumper system during a crash is conveniently evaluated by the load-displacement response in which the area under the corresponding load-displacement curves is a measure of the energy absorbed.

For low velocity crashes, the car structure behind the bumper system should stay undamaged. The maximum impact load transmitted through the system therefore has to be limited. The ideal crash protection system has a load-displacement response like a step function, i.e. the load reaches the maximum allowable value as rapid as possible and remains there throughout the crash.

The various simulated load-displacement responses for the bumper investigated in this work are shown in Figure 9. In addition to the three cases based on the forming analyses, the results from one simulation using the nominal geometry (CAD model) and one experimental test are also shown.

The displacement is measured from a point in space corresponding to the 'point of first contact' between the barrier and the nominal geometry.

Looking at the various load-displacement curves, is seems clear that all of them follow more or less the same trend except for the differences in 'starting point'. Furthermore, it can be realised that the initial shifts in displacement correspond well

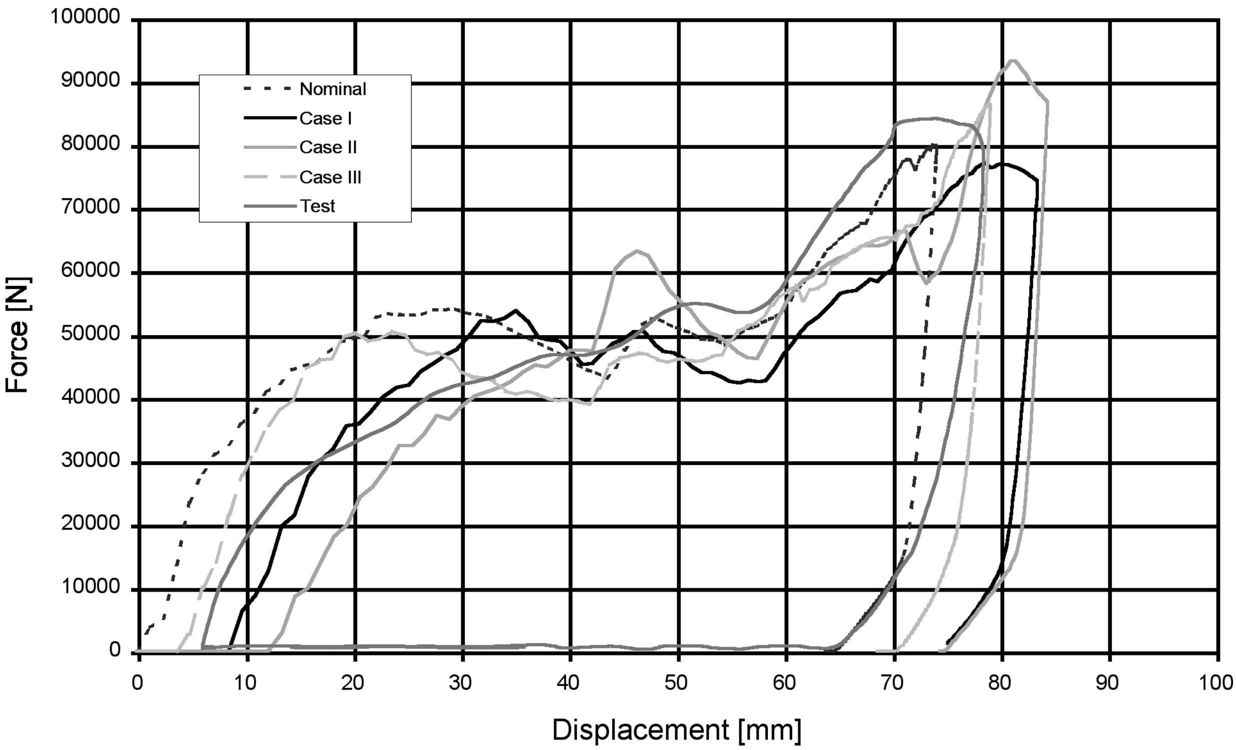

Figure 9: Load-displacement curves obtained by simulations and testing.

with the differences in section heights as commented above in the process simulation part. Since it is the practically the same amount of energy that is absorbed (i.e. initial kinetic energy of barrier minus final kinetic energy of the car), the loss in energy absorption in the initial phases of the crash leads to an additional penetration of the barrier into the car. The barrier's penetration into the car may have a significant effect on the level of damage inflicted to many of the important parts situated just behind the bumper (radiator, lights, etc.).

Apart from the amount of car penetration, the various cases studied gave load-displacement responses with only marginal differences. Based on the relatively significant differences in geometry, this result may seem somehow surprising. However, looking at what actually takes place during the crash may give an explanation. Figure 10 shows the bumper after the crash and again it is seen a very good correspondence between test and simulations, particularly on the simulation based on 'real' geometry (Case I). It is further seen that the swan's neck area of the beam has undergone more or less a rigid body rotation around the inner edge of the attachment plate. That may indicate that the regions exhibiting the largest geometrical variations, only to a limited degree have been active during the crash.

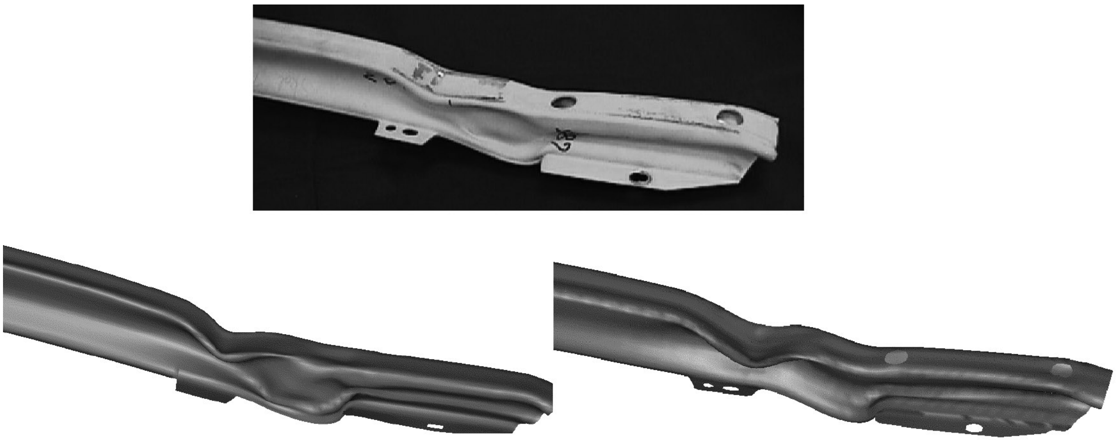

Figure 10: Comparison of deformations after crash for the test (above), simulation based on Case I geometry (left) and nominal geometry (right).

Conclusions

The present paper has shown an example of how LS-DYNA is used in development of products manufactured from bent aluminium extrusions. Particular focus has been put on demonstrating the advantages of integrating the product and process development activities. In addition to the many advantages of performing product and process simulations in general, the main benefits of the integrated approach demonstrated above, can be summarised in the following items:

- Increased accuracy in the product performance evaluation since a process simulation may give better predictions of how the real product is going to look like.
- The demonstrated approach may enable the optimum choice of process for optimised product performance.
- Reduced development times, e.g. by reducing number of iterations (design loops) needed for achieving satisfactory product performance.
- Support to CAD modelling.
- Enables virtual product development.