On Applications of Adaptive Strategies for General Shell Structures in Crashworthiness Analysis Using LS-DYNA

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Abbreviations:
FE: finite element
CD: Central Difference scheme

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ABSTRACT

Adaptive strategies are nowadays applied in a rather standard fashion in linear static analyses where reliable global and local estimators are available for many problems [22],[23],[5]. Considerable progress has been achieved for nonlinear problems [14], [4][8][9][13][17], also involving contact [21], because fairly reliable estimators exist, resulting in efficient procedures. However, for transient loading only limited success has been achieved so far [19],[20],[15],[11][12]. This is due to the fact that inertia effects and time integration schemes introduce additional complexity and approximations. As a result, no reliable error estimation is yet possible for large deformation dynamic problems such as metalforming and crashworthiness analyses. Adding to the difficulties is the complexity of the structures to be analyzed. Crashworthiness models violate, at least in parts, the continuum mechanics approximations such as multiple shell connections, spotwelds or shell-beam connections. Although proposals for the adaptive static analysis of composite shell connections exist [15], these cannot easily be applied to dynamic problems. In particular, the a-priori definition/detection of such non-continuous parts is a difficult task and contact regions need high resolution to achieve reasonable error estimation. Furthermore, there is no reliable error estimation possible for the very efficient and simplified shell elements with reduced integration and hourglass control - the "work-horse" in crashworthiness analysis. Nevertheless, some standard error indicators have been implemented and tested for some large deformation problems in LS-DYNA with some success [9].

As a consequence, for very general, large scale crash models in industrial practice currently only adaptive procedures remain which use error indicators based on simple ideas such as geometrical relative deformations [3]. These methods have to be combined with adaptive meshing schemes which allow only a certain level of refinement due to efficiency reasons. Additionally, the refinement has to be restricted to various points in time. In particular for deep drawing applications, it often appears to be very beneficial to step back in time and restart the analysis with an adapted mesh at a previous point in time.

LS-DYNA [7] has been recently enhanced by the capability to allow adaptive schemes for certain type of shell connections. In addition, it was observed that it is very effective to refine the mesh in metalforming applications prior to contact with small radii. The introductions of these so-called look-ahead algorithms limit the number of back-steps in time to almost zero.

This contribution highlights these new features in LS-DYNA. The numerical examples range from metalforming analysis, simple buckling analysis of a structural member to a complex crashworthiness model. The merits and the limits of the currently available methods in LS-DYNA are illustrated. This may lead to further insight on how future efficient error estimators could be developed on a sound mathematical basis, even for large deformation problems with high complexity. Some hints are given to use the implemented indicator and the adaptive meshing efficiently improving the quality of the analyses.

INTRODUCTION

The standard error estimators [1][22][23] - in the case of nonlinear problems rather error indicators - have proven to be applicable with success to problems in large deformation analysis [8][18]. However, at a closer look the limits of the various indicators for very general applications are clear. In transient analyses the kinetic effects are often neglected [19][20][11], contact errors cannot be appropriately taken into account [21], errors in the constitutive model and the constitutive integration are not consistently considered and the correct geometry is not used for the deformed states [13][18]. In addition complex composite type structures cannot be handled consistently with error measures resp. consistent indicators [16]. Such model problems are arbitrary shell intersections, model connections between parts as e.g. spotwelds or shell-to-solid connections or arbitrary constraints and rigid bodies. The problem class for which most of the current indicators can be applied is set up fairly homogeneous such as sheets for metalforming or crash girders, which have a small radius at the edges of the rectangular cross section and can be thus considered as continuous shells.

In large model analyses with explicit time integration it is also important to limit the number of error evaluations for efficiency reasons. For contact problems in sheet metal forming there is the question, whether a refinement on the current FE mesh takes place and the analysis continues – the so-called 1-pass strategy - or if necessary, then the analysis starts again at a previous time step – the so-called 2-pass strategy, or if a so-called look-ahead strategy is preferred. The latter checks for small radii in the tools and performs a refinement before contact takes place, avoiding artificial penetrations in the refinement process to some extend. In addition it is questionable, whether the data transfer among the meshes is not introducing a major error, such that an analysis with the refined mesh from the beginning of the analysis is preferable. Then the geometrical error of the initial mesh could be reduced, if the refined mesh is projected onto the correct CAD geometry and a reanalysis is performed.

Finally the improvement of the efficiency of the adaptive analysis by mass scaling is investigated and the impact on the results is discussed.

APPROACH

Error estimation and adaptivity with explicit time integration

As explicit time integration is usually applied to problems with transient loading, it is an open question if kinetic aspects can be neglected for error estimation. This topic is discussed by Neumann, Riccius, Schweizerhof [11] in detail for shell structures. The result is that mainly for wave propagation problems the kinetic terms have to be considered in the spatial error estimation. For slower processes, such as the large deformation processes in impact or crash of shell type structures, the mass discretization is ab initio better than the stiffness discretization, once refinements take place. This is a very general observation which still lacks proof for crashworthiness analyses, however a re-analysis with a refined mesh and comparison of the stresses should reveal the limits of such an approach in unknown situations as e.g. crushing of a beam.

Spatial Adaptation and error estimation

For the general discussion of spatial adaptation and error estimation we refer to a forthcoming paper [24] and focus on the features currently implemented in LS-DYNA. Some alternative error measures resp. indicators and their application in sheet metalforming are applied in a contribution by Mosfegh, Li and Nilsson [10].

For explicit programs, however, it has to be noted that, if the analysis is performed with elements with reduced integration and hourglass control [2] [6] - as mostly in LS-DYNA, the error estimation and the results are not reliable, if the hourglass forces are beyond a marginal value. Thus, the hourglass energies have to be checked carefully once an adaptive analysis is performed with both the fully and selectively reduced integrated shell elements.

The simple estimation strategy in LS-DYNA originally proposed by Belytschko and coworkers [3] is based on geometrical errors comparing the angle deformation between elements. Though this indicator is certainly not capturing high stress gradients resp. large strain gradients very well or contact stresses at all, it is applicable in all types of models even between intersecting parts. Thus it is a very robust indicator, which is of extreme importance in complicated models. It also leads to refinements in areas with some hourglassing which is often beneficial, in particular in cases with overly coarse contact surfaces.

Mesh adaptation
In large deformation analysis with shell elements the element forms mostly do not change very much resp. only in rare cases, thus strategies based on pure subdivision for refinement are sufficient for many analyses. Nevertheless, in the long term a complete remeshing capability – as it is available for solids - may be necessary for very general situations. Currently, LS-DYNA [7] contains a subdivision strategy dividing a quadrilateral or a triangular element in 4 subelements with similar shape producing hanging nodes to those regions that remain unrefined.

For standard error indicators, based on relative measures refinements are usually performed such that the local error is below a given tolerance, once a refinement was necessary. In LS-DYNA only a one-level refinement is allowed in one step, in order to keep a one-to-two neighbor rule - an element side can contain only one hanging node; otherwise the adjoining element has to be refined too. For the simple error indicators, two problems exist: First, it is not known how many levels of refinement should follow, once the indicator indicates that the error tolerance is passed. Second, the indicator value is an absolute value, completely problem dependent. Thus a trial analysis with a coarse mesh seems to be advisable to get a rough idea for a reasonable measure. Only experience with similar simulation problems will make this "ad-hoc" error measures successful. Then also a reasonable number of refinement levels as well as the time between refinements can be set.

Time step-size adaptation
Contrary to most implementations of implicit integration schemes which do not require a consequent adaptation of the time step-size explicit schemes such as the Central Difference method are depending on the time step size for algorithmic stability, the CFL condition. Thus the time step is continuously adapted to the size of the elements reflecting the change in the highest frequency in the structure.

Computational Effort and Improvements, Mass Scaling
Consequently, with any spatial adaptation also the time step-size is modified, if the highest frequency of the newly created smaller elements is beyond the highest frequency of the previous mesh. Thus, each subdivision leads to a reduction of the time step size by 50%. If the computing time is considered, this means that the effort for the unmodified mesh parts increases by 100% and for the modified part with subdivided elements by 700%. The latter larger number is due to the fact that instead of one element four have to be computationally handled and then two time steps are needed instead of one previously. If a further subdivision is considered the effort increases by the same factors.

In order to avoid such an increase various measures are suggested in the literature. The consistent approach would be to look for subcycling schemes with all the difficulties involved. Such a scheme is in principle also available in LS-DYNA. A much more efficient but rather ad-hoc approach is to use mass scaling. This means that the density of the subdivided elements is modified, such that the highest frequency remains identical to the previous large element. Thus after a one level refinement the density has to be multiplied by a factor of four. If only a small number of elements is affected by such a change in the simulation model, the overall behavior of the structure is not modified; this is also the case for rather constrained problems such as sheet forming between dies and matrix, where the motions perpendicular to the contact are considerably limited. However, for crashworthiness applications the increase in mass might be overly large and artificially increased impact forces or vibrations may result. Thus this approach has to be used with great care and the added mass has to be checked resp.

some reanalysis have to be performed with smaller time steps and non-modified density. The savings concerning computer time are mostly far beyond 50% compared to an analysis without mass scaling.

It must be noted that the efficiency concerning memory requirements is rather high in LS-DYNA, as dependent on the growth of the problem size due to refinements any memory allocation and disk space usage are dynamically determined.

DISCUSSION OF RESULTS

Metal Forming Simulation

Within this fender deep drawing simulation the effectivity and efficiency of the standard mesh refinement indicator in LS-DYNA based on simple angle change and a) applied with the 1-pass and b) alternatively with the 2-pass strategy and c) a combination of the angle-change indicator with the look-ahead strategy without stepping back in time is investigated. The initial mesh of the blank contains 19636 elements of the Belytschko-Tsay type with one-point integration and stiffness hourglass control. In order to construct a reference solution the finest mesh created by the look-ahead strategy is taken and re-analyzed from the beginning without mass scaling and adaptation. Comparing the plastic strains at the mid-plane of the blank at the final stage of the deformation process shown in figure 1, we can conclude that - as expected – the look-ahead strategy proves to deliver the best results. This is firstly due to the finest mesh used and secondly due to the effect that by the refinement strategy interpenetrations in contact due to overly late refinements can be avoided to a large extent.

The efficiency of the different strategies is compared in Table 1. Clearly the 1-pass strategy needs less CPU time, however, though the look-ahead strategy contains about 25% more elements than the other two methods it needs only about 8% more time than the 2-pass strategy. The final meshes differ quite considerably as shown in Figure 2 for the look-ahead and the 2-pass strategy.

Strategy	CPU- Time [Min]	# of Elements
1-Pass	40	42 484
2-Pass	77	42 688
Look-Ahead	83	51 451

Table 1. Sheet metalforming simulation of fender. Comparing the efficiency of different refinement strategies

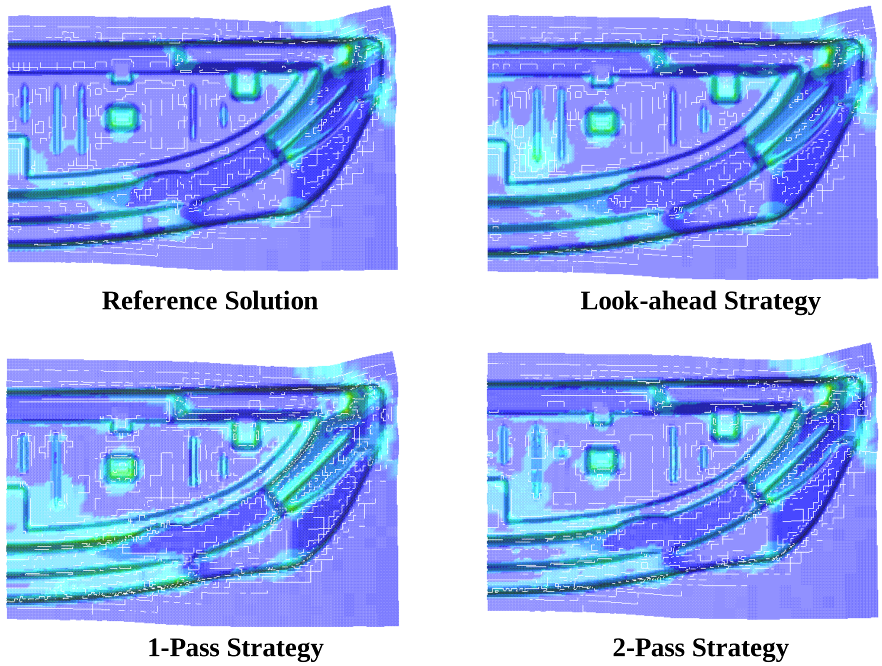


Figure 1. Sheet metalforming simulation of fender. Plastic strains in mid plane of blank at final state of deformation process. Comparing different refinement strategies.

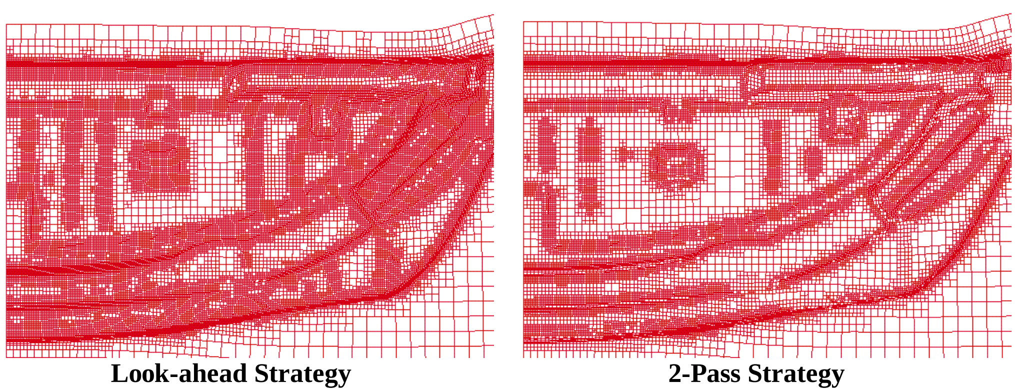
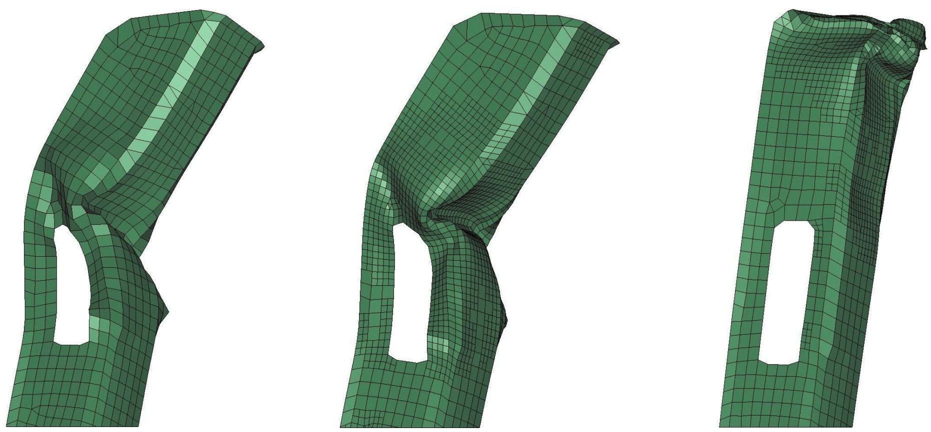


Figure 2. Sheet metalforming simulation of fender. Meshes at final state of deformation process. Comparing different refinement strategies.

Buckling of a Crash Girder under Transient Loading
A crash girder within an automotive structure is taken to compare adaptive strategies concerning the 2-Pass Strategy and different refinement levels and a complete restart with the final adapted meshes. In addition, the influence of the element type – here uniformly reduced integration with hourglass control (Belytschko-Tsay = ET2) and full integration with assumed shear strain interpolation (ANS = ET16) - on the buckling behavior is investigated. The initial mesh contains 2432 shell elements with elasto-plastic material. The loading is via a prescribed displacement time history for the boundary nodes at the longitudinal ends of the girder.



Coarse Mesh	Adapted Mesh	Adapted Mesh
Bel.-Tsay (ET2)	**Bel.-Tsay (ET2)**	**ANS – ET16**

Figure 3. Girder under longitudinal compression. Final state of deformation process with level 2 adaptivity. Comparing the influence of different element types.

Comparing the behavior of two different element types with adaptivity, see Figure 3 using a two-level refinement – allowing the elements to be subdivided once – a considerably difference in the deformation modes is found, though the time history for the cross-section force is not differing much, see Figure 4. As expected, the fully integrated element behaves stiffer than the Belytschko-Tsay element.

The difference between a two-level and a three-level refinement is visible, but was found to be rather unimportant for this example and is omitted for brevity reasons. More interesting is the result that the behavior is changing depending on the refinement as is found for the analysis with the assumed strain element (ET16), if the adapted mesh from the simulation with the Bel.-Tsay element (ET2) is used from the beginning. In the latter case, the deformation shape is almost identical to the behavior of the girder using ET2 with adaptation. Such results are well known for buckling problems which are often sensitive against geometric imperfections as e.g. introduced by a different meshing.

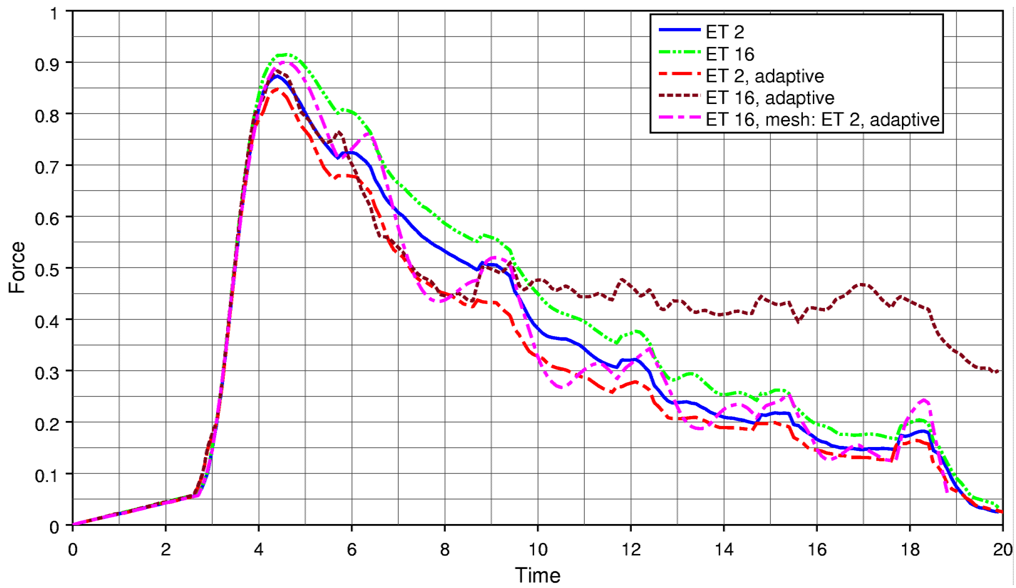


Figure 4. Girder under longitudinal compression. Time history of cross section force. Comparing different element types, adaptive meshing and restart with adapted mesh.

Roof Crush Under Quasi-Static Loading

This roof crush problem was discussed in [25] under the aspect of quasi-static analysis, mass scaling and the influence of the choice of the shell element type on the final result. The initial mesh consists of 27712 shell elements and 26115 nodes. All model points at the lower boundary are fixed. For the contact within the roof, internal contacts of type 13 were applied. The loading by the steel plate with 10 mm/s is simulated with 2000 mm/s, which is discussed in detail in [25]. No friction was assumed between the roof and the loading plate. The analysis was performed up to about 120 mm resp. 170 mm.

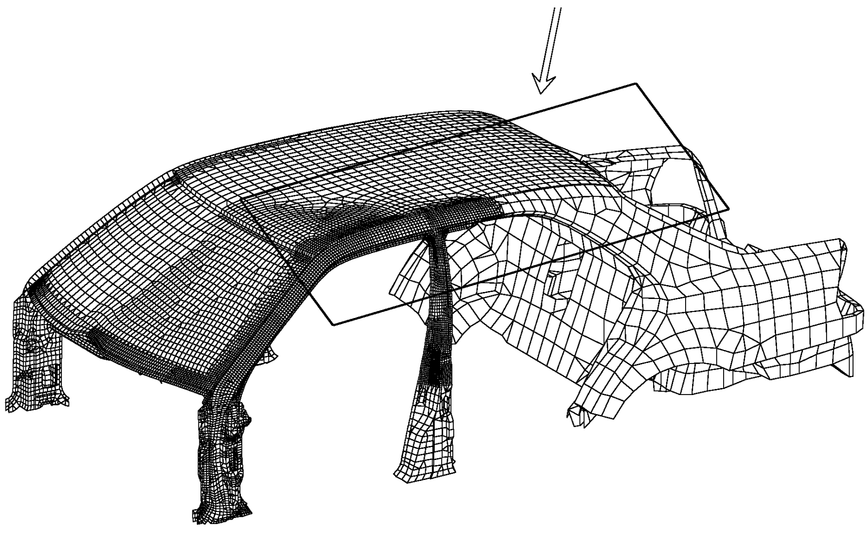


Figure 5. Roof crush analysis. Mesh, loading plate and loading direction (arrow).

The following results discussion is concerned with the influence of two different levels of adaptivity – one-step (two-level) and two-step (three-level) refinement - on the results, see Figures 6 and 7. The deformation patterns for both levels are definitely different from the initial mesh with 27712 elements and show also some difference between the two levels.

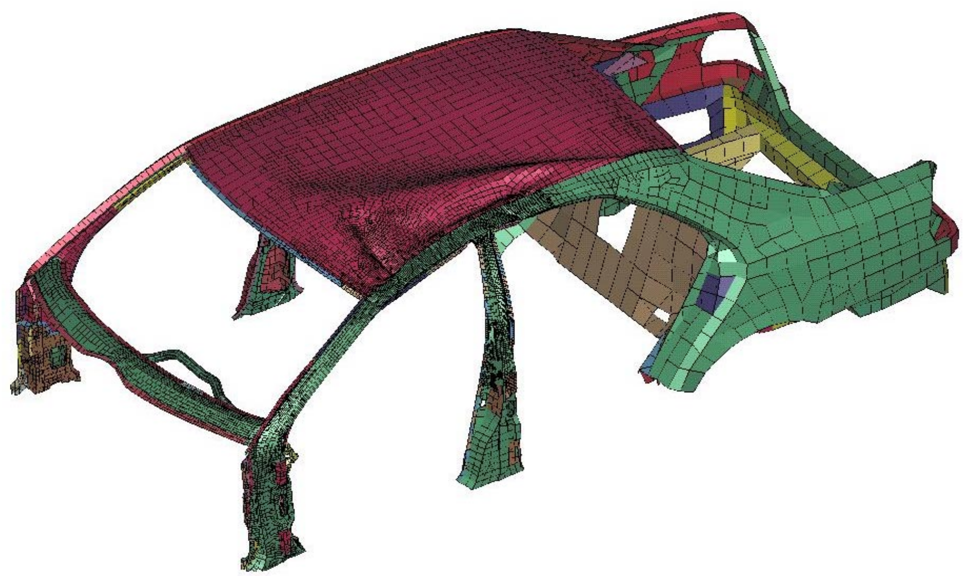


Figure 6. Roof crush analysis with Belytschko Tsay element. Final deformation state. Adaptive two level refinement with 42 252 elements.

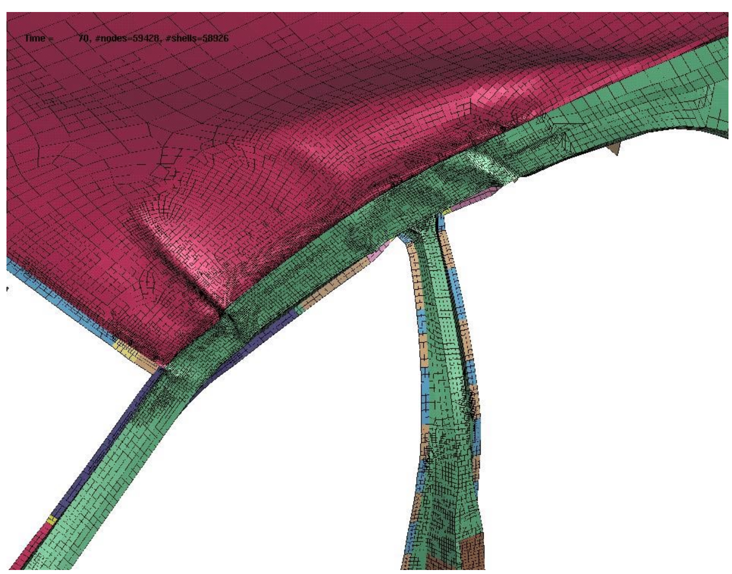


Figure 7. Roof crush analysis with Belytschko Tsay element. Detail of final deformation state. Adaptive three level refinement with 58 926 elements.

The comparison with test data, shown here for the contact force at the rigid wall, reveals that the analysis is rather stiff for the beginning of the simulation, indicating that some refinement may be advisable already very early in the simulation. Adaptivity leads to rather soft results for the Belytschko-Tsay (ET2) element and the ANS (ET16) elements with refinement level 3 appear to be very close to the test curve. However, it must be noted that this is only one test result and can therefore only be used as a first comparison for an analysis. In particular, the sharp peak in the test curve must be identified with an event within the process, respectively the repeatability of the test results is also needed.

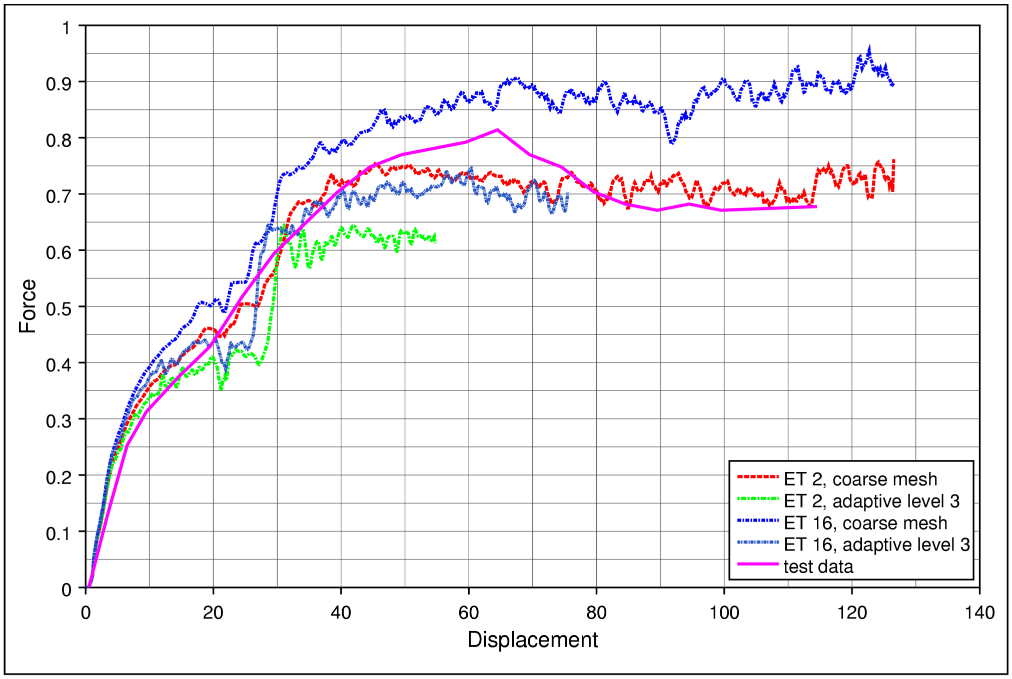


Figure 8. Roof crush analysis. Contact force at rigid loading plate. Variation of refinement level and shell element type. Comparison to test data.

If the adaptive analysis is performed without any time step modification, the mass added in the refinement steps because of mass scaling may lead to some peak in the force-deformation curve. Thus the step-size had to be reduced within the adaptive analysis by almost 50%, which was done after observing the high mass increase and after some artificial peaks had been noticed following the refinement.

CONCLUSIONS

Adaptive FE simulations have been performed with the rather simple strategies currently implemented in LS-DYNA. They reveal the problems involved in adaptive analysis when new meshes have to be created in contacting regions such as metalforming, where reanalysis with a refined mesh seems to be advisable. Alternatively the ad-hoc look-ahead strategy proves to be a very good second-choice. The buckling analysis of the girder showed the sensitivity against mesh modifications during the analysis and the final example for roof crush underlined the importance of refinement for such complex problems. It also reveals that the underintegrated elements behave rather soft in membrane dominated problems. It becomes also visible that as known the “angle”-indicator cannot capture the necessity for mesh refinement in the initial state with small deformations. This must be kept in mind for additional mesh improvements.

As mass-scaling is per default applied with mesh refinements, the mass increase and the structural behavior following the refinements have to be carefully checked in order to avoid false results due to over-emphasizing efficiency. Then time step size reductions have to be performed according to the refinements.

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