Roof-crush Analysis of the Volvo XC40 Using the Implicit Solver in LS-DYNA®

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1 Introduction

During the development process of a new platform or car model, each design iterate is subjected to a large number of load cases, both dynamic as well as static. At Volvo Car Corporation, this process is almost entirely carried out using virtual testing by finite element analysis. The amount of physical prototypes is reduced to a minimum, and in many cases physical testing is limited to the component or sub-assembly level. Still, the final design must pass a number of physical tests and legal requirements, where roof crush is an important test of the structural integrity of the cab. The purpose of the FMVSS roof crush test is to "reduce deaths and injuries due to the crushing of the roof into the passenger compartment in rollover accidents" [6].

At Volvo Car Corporation, occupant safety is a fundamental element in all development projects since the start of the company, and the Volvo XC40 received a 5-star rating when tested by Euro NCAP [7]. The roof crush resistance is important with relation to safety in case of a roll-over accident, since the structural integrity of the car body makes the final line of defense, but many safety systems will interact in this case, from driver assist systems to electronic stability systems and restraint systems.

The roof crush test will induce high stresses in many structural parts of the car body, for example the A-, B- and C-pillars, window frame and roof. This means that the analysis must be carried out meticulously, since the roof strength requirement may set design limits for many structural parts. Also new design concepts, such as composite roof panels or panorama glass roofs, imply new challenges for the roof crush analysis.

The testing procedure according to FMVSS 216 [6] is specified as quasi-static (the time to complete the test is minimum 10, maximum 120 seconds), but has traditionally been run in explicit LS-DYNA in only a fraction of this time. From this viewpoint the roof-crush load case would be a typical application of implicit analysis, allowing the simulation of the test to get closer to the real test procedure. As a part of the ongoing method development work, it was decided to evaluate also the implicit technique, using the Volvo XC40 as a benchmark case.

A previous study [5] indicated that it is possible to re-use FE-models originally created for crash load cases also for quasi-static load cases using the implicit solver in LS-DYNA with a reasonable modification effort. A previous study on implicit roof-crush analyses in LS-DYNA [1] indicated good correlation to explicit analyses, as well as reasonable performance with respect to solution time. Also, the publicly available examples [2][3] of implicit roof-crush analyses served as great inspiration in the present work.

2 From explicit to implicit

Normally, the roof crush analyses at Volvo Car Corporation are performed by LS-DYNA explicit, using FE-models originally prepared for side impact load cases. In this section, the procedure for modifying such an FE-model for implicit quasi static analysis is briefly outlined. In all, this is a rather convenient procedure.

The shell element section definitions were conveniently switched to a fully integrated formulation (element formulation 16) by use of ISHELL on ***CONTROL_IMPLICIT_EIGENVALUE**.

One global single surface contact definition was used, which also is the common approach to contact definition in explicit crash models. However, for the implicit analysis, the dedicated MORTAR [9] – contact was used: ***CONTACT_AUTOMATIC_SINGLE_SURFACE_MORTAR**. For the global tied contact, the IPBACK – parameter on optional card E was activated. By this, a penalty-based back-up tied contact is automatically created for those slave nodes that are prohibited to be tied by the constraint tied approach, due to for example rigid body constraints. The purpose of activating IPBACK in implicit analyses is to minimize the risk of unconnected regions due to missing tied contacts.

The loading device was re-modelled from a rigid wall definition to a meshed part using shell elements and rigid material (*MAT_RIGID), in a similar way as in Ref. [1]. This makes it possible to use the

MORTAR contact also between the load application device and the car. A prescribed displacement was applied to the loading device. The loading sequence was somewhat accelerated compared to the requirement of Ref. [6], but still much slower than in an explicit analysis. The purpose of increasing the loading rate was mainly that it seemed that some solution time could be gained by this also in implicit. However, the effect of loading rate on solution time and simulation results in the implicit approach is a topic for further investigations. The loading was divided into one initial phase with a high loading rate (ten times the requirement) and a final phase with a slightly lower rate (still twice the requirement), see Figure 1. This approach was based on some initial tests, which showed that it was necessary to reduce the loading rate at some point in order to obtain a good quality force signal. Constrained boundary conditions were applied to the underside of the car body sills.



Fig.1: The loading sequence was divided into one initial phase with high loading rate and one final phase with slightly lower loading rate. The purpose of this was to minimize solution time while maintaining a good quality force signal.

Some minor modifications were made to the material models, where all strain rate effects were disabled by setting IRATE = 1 on ***CONTROL_IMPLICIT_DYNAMICS**. Also, most material failure options were de-activated, and user defined materials were replaced by standard LS-DYNA materials (MAT_24). Most of these material changes were easily carried out using the material models already existing in the Volvo Car material database. The user defined material models are used at Volvo Car to predict material failure in different components, such as the B-pillar made of press-hardened boron steel, but also for welds. Ideally, material failure should also be included in the implicit analyses in order to obtain realistic results. Currently, investigations are being carried out in order to ensure full functionality of the user defined material models also for large-scale implicit analyses. Tests using smaller models indicate promising results.

During the process of developing a methodology for implicit roof-crush analyses, a step-wise approach was applied. Initial testing - of for example the loading rate and some control card settings - was performed using simplified models with only a few features. As the critical issues were identified and resolved, more complex FE-models were analyzed, with help of the gained experience. Three different FE-models of the XC40 were used, with increasing degree of complexity, see Table 1 and Figure 2. In the first stage a BiW without windscreen and cross car beam (CCB) was analyzed. In the second stage, the windscreen and CCB was added, and in the third stage a rather complete model including doors and tailgate was analyzed. In the third stage, when doors were added, some minor re-modelling was applied to the door hinges and door handles. The original explicit FE-models were intended for side impact analyses, and thus the complete door handle mechanism was modelled with moving parts. In order to make convergence easier by eliminating possible rigid-body modes inside the mechanism (which also were of no importance to the roof crush load case) the door handles and lock mechanism was greatly simplified – in principle replaced by a constrained nodal rigid body. Also, the attachment bolts of the hinges and the hinge pins were re-modelled. Pre-tensioning of relevant bolts was included, see further Ref. [11] for details on bolt pre-tensioning in LS-DYNA.



Fig.2: The three different FE-models of the XC40 used during the method development project. The left image shows the first stage with only without windscreen and CCB. In the second stage (middle image) the windscreen and CCB were added. In the third stage (right image) also the doors and tailgate were added.

The roof-crush analysis can be carried out on a simplified complete car model, where non-structural parts like seats and interior trim can be omitted, but still a typical model size will be somewhere between 3 to 5 million elements. The model size of the most complete XC40 version in the present project was 2.8E6 elements, see also Table 1.

2.1 Control card settings for the roof crush analysis

The basic control card settings for non-linear implicit analyses from Ref. [4] were combined with the recommendations of Appendix P of the LS-DYNA keyword manual [8], to provide a good starting point for the control cards. In addition, the shared experience of Refs [1–3] provided great input. The key success factors were to use implicit dynamics (*CONTROL_IMPLICIT_DYNAMICS) and solution settings (*CONTROL_IMPLICIT_SOLUTION) for full Newton (ILIMIT = 1) combined with a conservative displacement norm measure (DNORM =1). Also, a convergence criterion based on the absolute norm of the force residual vector was activated by setting ABSTOL = -0.100. This means that LS-DYNA will detect convergence if the norm of the force residual vector is below 0.1 kN in this case. The purpose of this setting was to speed up convergence during the initial steps, before the load application device contacts the car. On *CONTROL_ACCURACY, the implicit accuracy flag (IACC) was set to one, activating a number of accuracy enhancements for implicit analyses. Automatic time-step control (*CONTROL_IMPLICIT_AUTO) was active, using a rather conservative time stepping scheme, combined with a load curve to limit the maximum time step as a function of problem time. To be more detailed, the following settings were applied:

*CONTROL_ACCURACY										
\$#	osu	inn	pidosu	iacc						
	1	4		1						
*CONTROL_IMPLICIT_GENERAL										
\$#	imflag	dt0	imform	nsbs	igs	cnstn	form			
	1	0.50								
*C0	*CONTROL_IMPLICIT_SOLUTION									
\$#	nsolvr	ilimit	maxref	dctol	ectol	rctol	lstol	abstol		
	12	1	65	1.E-2				-0.100		
\$#	dnorm	diverg	istif	nlprint	nlnorm	d3itctl				
	1	1	1	3	4	1				
\$#	arcctl	arcdir	arclen	arcmth	arcdmp					
\$#	lsmtd									
	4									
*CONTROL_IMPLICIT_AUTO										
\$#	iauto	iteopt	itewin	dtmin	dtmax	dtexp				
	1	45	10	1.E-6	-700.					
*CONTROL_IMPLICIT_DYNAMICS										
\$#	imass	gamma	beta				irate			
	1	0.6	0.38				1			
*CONTROL_IMPLICIT_EIGENVALUE										
\$#	neig	center	lflag	lftend	rflag	rhtend	eigmth	shfscl		
\$#	isolid	ibeam	ishell	itshell	mstres	evdump	mstrscl			
			16							

In order to effectively solve problems of this size using the implicit solver in LS-DYNA, it is recommended to use the hybrid implementation [10]. The command-line driven submit-script used at Volvo Cars was modified, making it possible to easy submit also hybrid jobs to the VCC Cluster.

3 Results

In this section, some results from the roof-crush analyses of the three different configurations of the Volvo XC40 are presented. Some comparisons to explicit simulation results are also made. The implicit analyses were run using hybrid/LS-DYNA R10.1¹.

One of the principal results of a roof-crush simulation is the force vs. deflection curve. LS-DYNA offers many options for evaluating the force in this case. Either the force due to the imposed displacement can be evaluated (the **bndout** results) or the reaction force in the contact (**rcforc**) between the load application device and the car can be evaluated. Another option is to evaluate the reaction force from the fixed boundary conditions on the car sills (**spcforc**). Ideally, if static equilibrium is obtained, these forces should be equal. By comparing forces evaluated using these three methods, the solution quality as well as the amount of dynamic effects present in the simulation can be estimated. In the presented analyses, the maximum force difference was 16 % of the peak force.

The force (evaluated from the **rcforc** results) versus deflection curve for the three different configurations is shown in Figure 3. It can be noted that when the windscreen and CCB is added, the effect on the peak force is quite significant, while the effect of adding tailgate and doors gives a noticeable but smaller increase. A comparison of the deformed configurations is shown in Figure 4. The implicit simulation results from the most complex FE-model configuration were also compared to explicit results. The implicit and explicit analysis results show similar response up to the peak force value, see Figure 5.



Displacement

Fig.3: Force vs. displacement curves from implicit roof crush analysis of the three different configurations.

¹ Initial testing showed that much smoother force response was obtained using R10.1 than R9.3 in this case.



Fig.4: Deformation of the three FE-model versions. The top left image shows the BiW only. The top right image shows the version with added windscreen and CCB. The bottom image shows the version where also the doors and tailgate were added.



Fig.5: Force vs. displacement curves from implicit and explicit roof crush analysis of the most complete FE-model (including windscreen, CCB, doors and tailgate).

3.1 Implicit solver performance

In this section, some results with regards to the implicit solver performance are presented. It shall be noted that this is not a regular scaling study, since both model size and CPU count is varied simultaneously. Still, the results will give a basic impression of the required solution times. The solution times for the three studied configurations are compared in Table 1. For reference, the solution time for an explicit analysis of the most complete FE-model version is also presented. This explicit simulation was performed using mpp/LS-DYNA R10.1 single precision. The loading rate was 1 m/s, and the standard (non-MORTAR) contact definitions used for explicit analyses at Volvo Car Corporation was used.

The result that the explicit solution time in this case is significantly lower than the implicit, is in line with what has been presented previously [1]. This may to some extent be explained by that the roof-crush load case is very demanding for the non-linear implicit solver, since it is a highly non-linear problem, involving both local and global buckling, as well as material non-linearities and contacts.

		Solut		
Version	Number of elements	Implicit	Explicit	No. of cores
BiW only	1.6E6	75.3 h	N/A	196
Added windscreen and CCB	1.9E6	64.5 h	N/A	224
Added also doors and tailgate	2.8E6	73.9 h	2.05 h	448

	Table 1:	Overview of	model size	and solution	times
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4 Summary and conclusions

In all, the implicit solver in LS-DYNA now seems to have reached a state where it is becoming suited for large scale analyses in daily production use. The force results from the implicit analyses are in good agreement with the ones obtained from explicit analyses. The conversion of the LS-DYNA models originally prepared for explicit analyses is relatively convenient and only minor modifications are required. In all, the implicit analysis results show an interesting potential for the future.

One topic for future investigations is how to handle material failure. For explicit analyses at Volvo Cars, normally user material routines are used for material failure prediction by element erosion. Further investigations are required in order to verify that the same approach also works for large-scale implicit analyses. As an intermediate step, it would maybe possible to use a simplified failure criterion for the implicit analyses.

Another topic for future work may be to further improve the scalability of implicit LS-DYNA in order to reduce solution time and make even better use of the large-scale (over 1000 cores) analysis resources available at Volvo Car Corporation. Increasing the scalability of implicit in general is a topic for ongoing research and development at LSTC, see for example Ref. [12] where good scaling up to 8000 cores was obtained for a dummy jet-engine model.

5 Literature

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