CAE MODELING OF BOLTS FOR CRASH

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KEYWORDS – CAE, bolt, screw, modelling, material, automation, Ansa, LS-Dyna

ABSTRACT –
Reliable CAE crash results are crucial for Volvo Cars, in order to secure that the final products meets safety requirements and also the customer expectations to be leading in safety.

At Volvo Cars the introduction of new technologies and new materials, such as electrified vehicles, aluminium and new joining techniques creates a huge challenge in the ability to predict crash performance. One key area is the prediction of screw joint behaviour in CAE simulations, which are used to attach critical components that either should break away or withstand a certain load during a crash.

We count well over 30 groups of critical interfaces where crash performance is significantly affected by bolt performance in various load cases. Such bolted interfaces can for example be found in the battery box attachment to the car body in EV: s, bumper system, sub frame, suspension, engine mounts, steering system, cooler, seat-frames, body, doors etc.

To enable CAE driven development a work package was launched including:
- Material testing of standard bolt with 10.9 material
- CAE categorization of the bolt material in terms of material model and modelling method
- Validation of the method, both on component and on full vehicle level
- Ansa scripting in order to secure efficiency in the modelling phase

The outcome of the work is a reliable and efficient modelling technique of pre-strained solid meshed bolt generation through ANSA. Scripting in order to secure efficiency in the modelling phase and also a methodology to define the bolt material through physical testing and validation in simulation. The new modelling technique is used in upcoming Volvo cars and will be used onwards in all coming projects.

1. BOLT MATERIAL TESTING

Bolt material testing were performed through the help of colleagues at Geely Automobile Research Institute as well as Catarc Test Centre, China.

Test setups were defined with the purpose to collect required data to determine material parameters for subsequent material model development as well as validation. In this work, as a first step, the bolt steel material class was limited to 10.9 since this is the most commonly used class among interfaces significant for crash results. At time of writing 8.8 material model development is just being completed.

For the tests related to material parameter determination, although not most common in our cars, M14 bolts were chosen over smaller standards in order to have better control when machining the specimens and to improve mesh resolution of radii's and notches in subsequent FE representation. M12 and M8 were also included in subsequent validation bending testing.

Earlier investigations demonstrate a significant influence of the thread on bolt strength (2). Due to this, testing was performed both on shank and threaded part in tensile, bending and shear test.

Tension test:	
Tension test of flat specimen	- For determination of hardening curve
Tension test M14 bolt, all threads clamped	- For failure surface
Tension test M14 bolt, thread partly clamped	- For failure surface
Tension test on notched M14 bolt	- For failure surface
High speed test	
High speed test of small round specimens	- For strain rate dependency
Torque test	
Torque test of notched M14 bolt	- For failure surface
Shear test	
Shear test M14 bolt	- For validation
Bending test	
Bending test M14 bolt with two different clamping	- For validation
Bending test M12 bolt with two different clamping	- For validation
Bending test M8 bolt	- For validation

Table 1 – List of the different type of tests performed

Figure 1 – Pictures of samples from quasi-static and high speed tension testing (upper), as well as bending and shear validation testing (lower).

2. MODELLING METHODOLOGY

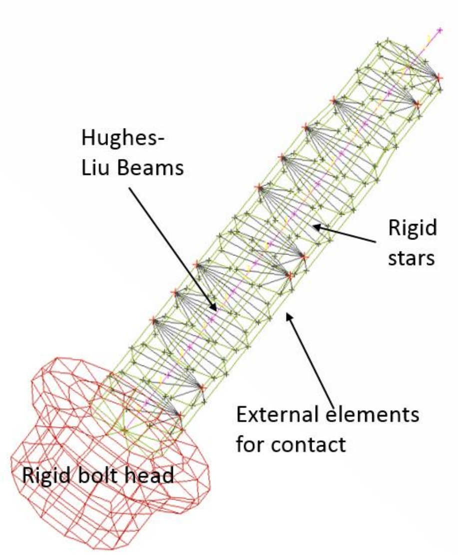
CAE categorization of the bolt in terms of material model and modelling method was performed with the finite element software LS-DYNA (2) and pre-processor ANSA (1). FE representation and LS-DYNA material model for the new bolt model were defined concurrently with test setups in order to retrieve correct output. Matlab were used to subsequently build up the material failure surface.

Ansa FE Model
Prior to the work described in this document, bolt strength was at Volvo Crash Department solely defined by Hughes-Liu beam elements with an elasto-plastic hardening curve (MAT_24) and plastic strain to failure calibrated against tension test. The latter only included when failure were to be captured. Contact was described through rigid stars connecting the centre beam with elements that represent external contact.

Main reason for this modelling technique was related to low cost and effort when building complete vehicle models. But there are obvious limitations, both with respect to the representation of the bolt geometry and force transfer to the bolt via contact against surrounding geometry, as well as the prediction of failure in other load states than tension or to some extent shear.

In order to maintain low modelling effort while at the same time increasing accuracy of bolt failure prediction it was decided that the model needed to be meshed with fully integrated hexahedron solids, use a material model that can handle multi stress state failure, and be automatically generated with the help of scripting in ANSA. Inclusion of bolt pre-tension is performed via a beam element, ramping up the force in axial direction by *INITIAL_AXIAL_FORCE_BEAM.

In order to handle contact in a proper way against surroundings and avoid edge-to-edge penetrations the bolt model is used in the context of a segment based contact (soft=2). An additional note is that the rigid bolt heads in the detailed bolts are currently being changed to deformable solid meshed counterparts in order to avoid stress concentration at the interface shank/head.



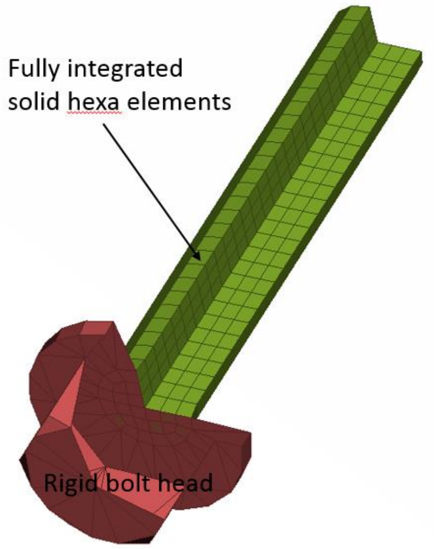


Figure 2 –Simple way of modelling bolts with beams and null solids for contact (Left). Corresponding new detailed solid hexahedron model (Right).

LS-Dyna Material Model

The LS_DYNA MAT_224/MAT_TABULATED_JOHNSON_COOK material model was chosen to describe the strength of the bolt. This is an elasto-viscoplastic material model where plastic failure may be defined as a function of stress state (triaxiality, lode angle), strain rate and element size.

The test setups were replicated in simulation, the stress-strain curve dependent on strain rate and failure strain as a function of stress state were approximated through inverse modelling. Repetitive tests were performed on a single test setup to ensure robustness of a particular result.

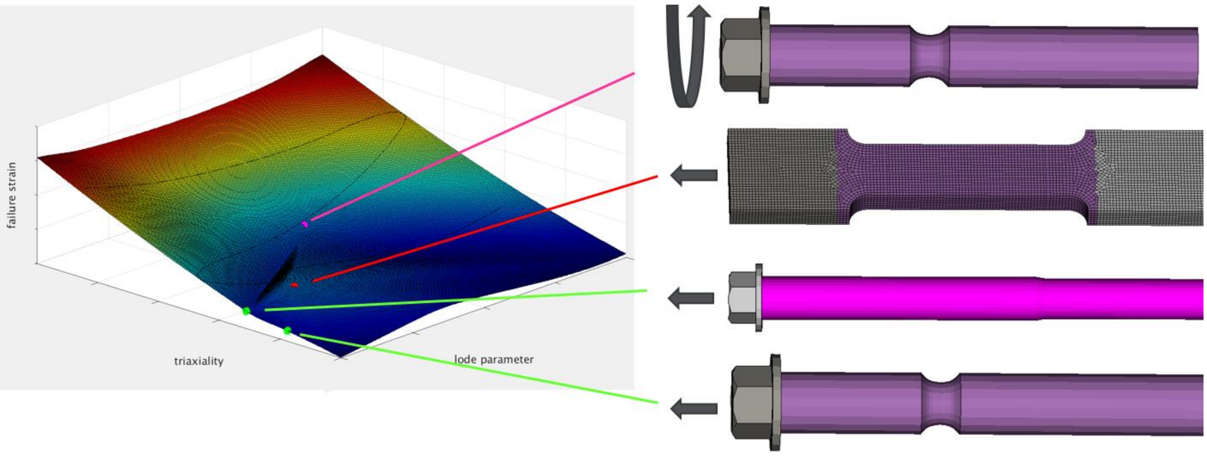


Figure 3 –A selection of the test setups that builds up the failure strain surface as function of stress state.

The material model was developed and validated with a mesh size ranging from 0.5 to 2 mm. Due to the relatively small element size, selective mass scaling (SMS) must be used on the bolts in full vehicle analyses for which the global time-step supersedes bolt element critical time-step.

As mention in chapter one it has been shown that the thread has a significant effect on the bolt strength (2). Results from tension, bending and shear test were performed both through the shank and the thread, confirming these findings. It was concluded early on that the material model would not be able to capture the actual stress state in the thread with the lower limit on mesh size of 0.5 mm. Instead stress state based on the modelled round geometry was used (same as shank), while a reduced effective sectional area was calculated in the thread based on diameter pertaining to a certain pitch. This assumption turned out to correlate well in tension, shear and bending tests.

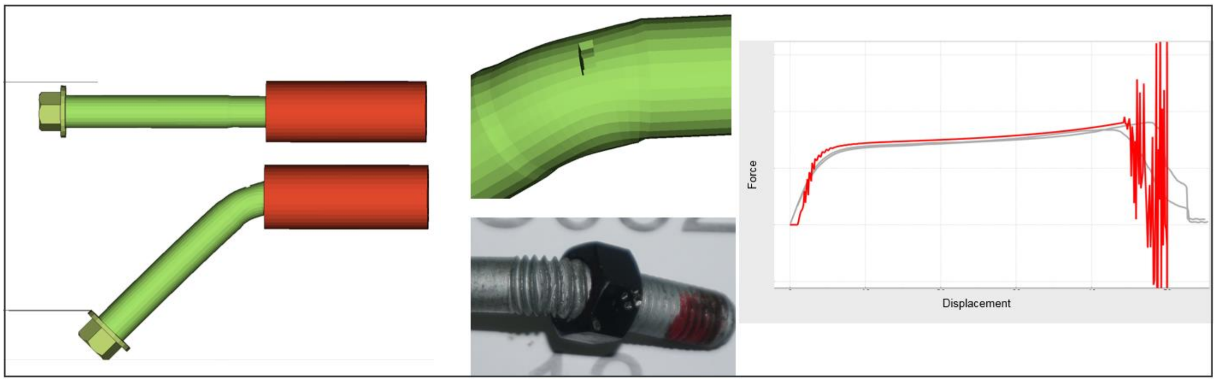


Figure 4 – Example of bending correlation testing (grey curves) vs replication in simulation (red curve).

3. AUTOMATED REALISATION IN ANSA

In order to be competitive in the automotive industry high demands are put on the CAE modelling phases where effectiveness and reliability are required. The automatized process to generate bolts by scripting in Ansa is therefore an essential step to be able to utilize the benefits of detailed modelled bolts. Without the possibility to easily generate the bolts throughout the vehicle model it would be difficult to use for inexperienced users, time consuming for all users and probably down prioritized more often than not.

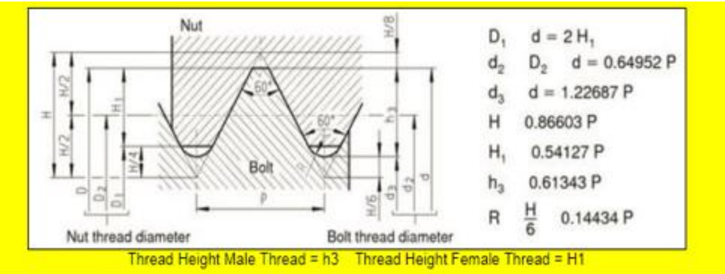
The resulting user script offers two possibilities to generate the bolts. Semi-automatic which requires some user input or fully automatic via CAD geometry together with information on specific bolts originating from Volvo Cars PLM system.

In the semi-automatic procedure the user has the possibility to add a custom bolt, specifying standard size, starting point and length vector as well as data such as shank vs thread length and thread pitch. In the automatic procedure these bolt attributes are generated automatically. Both versions of the user toolbar use shares the same base, but in the fully automatic version the procedure in the script looks as follows:

1. Identification of parts/components in a CAD model that make up bolts and nuts respectively.

2. Identification of bolt and nut pairs, dependent on if the nut lies within the bolt length and shares its orientation.

3. Extraction of PLM system bolt/nut attributes. Position, direction, length, diameter, shank/thread ratio, pitch etc.



	ISO Metric profile			External (bolt thread)					
Size mm	Thread Designation	Simple Thread Designation	Pitch mm	Class	Major Dia d=D max.	min.	Pitch Dia d2=D2 max.	min.	Minor Dia d3 max.	min.
14	M14x2	M14	2	6g	13.96	13.68	12.66	12.5	11.797	11.271
14	M14x1.5	M14x1.5	1.5	6g	13.97	13.73	12.99	12.85	12.344	11.93
14	M14x1.25	M14x1.25	1.25	6g	13.97	13.76	13.16	13.03	12.619	12.258
14	M14x1	M14x1	1	6g	13.97	13.79	13.32	13.21	12.891	12.59
14	M14x0.75	M14x0.75	0.75	6g	13.98	13.84	13.49	13.39	13.166	12.923
14	M14x0.5	M14x0.5	0.5	6g	13.98	13.87	13.66	13.57	13.439	13.257

Figure 5 – M14 example of attributes that may be read by the script.

4. Calculation of the effective sectional area in threaded part dependent on a specific bolt pitch.

5. Standardization of the resulting mesh in order to guarantee good quality solid mesh for bolt dimension ranging from M6 to M16

6. Adaptation of the mesh at the interfaces between bolt shank and bolt head (node-to-node connected) as well as against nut if present (same size and aligned in a way to ensure good contact).

7. Generation of pre-load element with force level based on bolt dimension and material grade, as well as type of pre-tension (torque-to-yield or a specific torque). The preload is transferred to the bolt at a location along the length where the actual force acts.

8. Part damping is applied to ensure a stable interface.

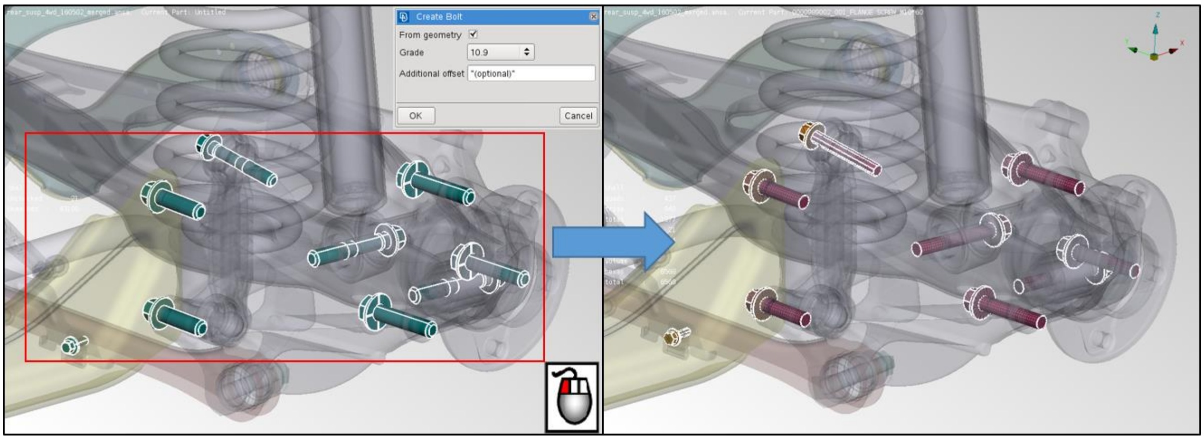


Figure 6 –Converting multiple CAD generated bolts in a rear suspension into detailed solid meshed counterparts, with a few clicks via the automatic bolt script toolbar. Correct attributes, material and pre-tension is also set by the script.

4. COMPONENT AND FULL VEHICLE VALIDATION

The detailed bolt model has been validated in three stages. Firstly by bending and shear validation tests mentioned in chapter one and three. Secondly by inclusion in correlation of component testing performed on door hinges as well as high voltage battery box. Thirdly as a part of continuous correlation work performed at Volvo Cars on full vehicle testing and simulation. One such example is suspension behaviour in small overlap load case where bolted joining plays a mayor role.

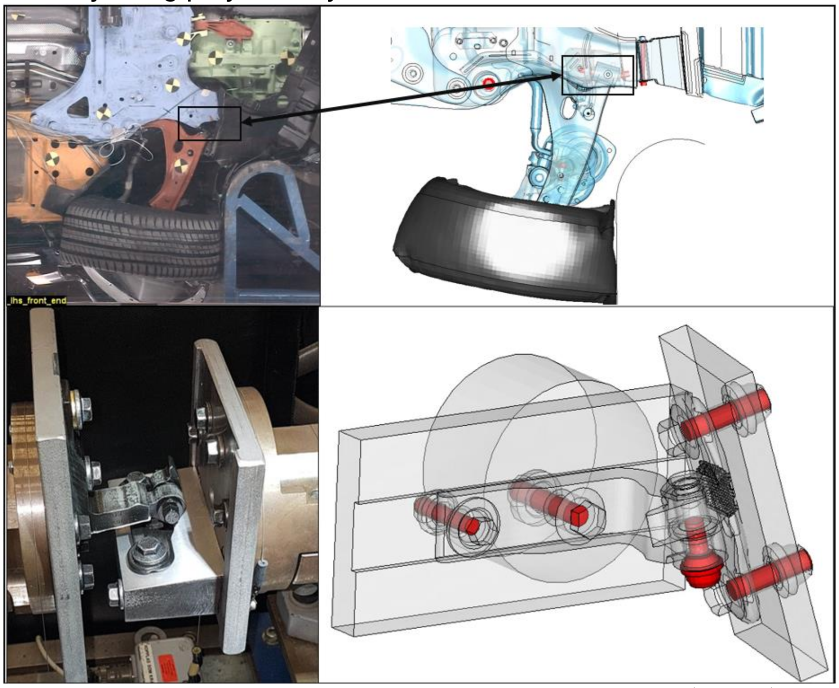


Figure 7 – Correlation of bolt model in small overlap (upper) and door hinges (lower).

5. CONCLUSIONS

The purpose and target of this work was to improve the bolt FE- and material-model to a level adequate to capture failure in critical bolted interfaces. The work was mainly broken down into creating a detailed solid meshed bolt in ANSA, various load state testing, and inverse tuning in LS-DYNA in order to build a material model that can handle multi stress state failure.

The resulting bolt model is judged to be able to predict both strength and failure in most relevant load states to an adequate degree. It is validated for element sizes up to 2 mm, beyond that size, stress states starts to differ in elements located close to failure for the same load cases, resulting in wrong failure strain.

The stress state in the thread is not capture due to limitation on mesh size in full car simulation, work needs to be done to establish the stress state in the thread grooves for future improvement. However the assumption to reduce the area at the threads to the minimum thread diameter shows adequate correlation in load conditions tested. A note is that the default contact point will be somewhat inward compared to reality but contact offset is included to put the segment back at the actual location.

The other main target of this work was to create an ANSA user interface to generate the bolts in an effective, easy to use, and standardized way. This was achieved by utilizing ANSA scripting to read both geometrical information from the CAD as well as bolt attributes originating from Volvo Cars PLM system. The result gives the user a very quick way of realising many bolts at once within a car sub-system. Greatly decreasing time otherwise spent on detailed modelling and risk of human error.

As an end note, due to the relatively complex and small bolted interfaces in a car, it is an absolute necessity to model the surroundings and its contact towards the bolt in critical interfaces as accurately as possible. Otherwise the detailed bolt benefit will largely be lost.

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