IGA 3D for bolt assembly using LS-DYNA R16

Franck Norreel[1], Pierre Glay[2], Julien Lacambre[2], Walid Gouaou[2], Ilka Schwarzer[3], Anantharam Sheshadri[4], Guillaume Lafitte[1]

[1]Stellantis, France
[2]ANSYS part of Synopsys, France
[3]Stellantis – Opel, Rüsselsheim, Germany
[4]Stellantis, US

1 Abstract

As Stellantis is targeting a drastic reduction of physical tests, all types of joints have not only to be able to correlate physical tests but also to predict them. For bolt fasteners, FE representation does not allow perfect results; indeed, while 3D meshing of bolts improves assembly representation, mesh dependency and mass scaling remain challenging.
In parallel, initial deployment of Iso geometric Analysis (IGA) for shell structures at Stellantis is delivering promising results, allowing to guarantee a better precision and continuity of result fields.
Target of this paper will be to clarify FE limitations and to investigate IGA technique for 3D representation of screws.

2 Introduction

In FE models, representation of joints is a key factor for an optimal predictivity. For bolts, not only forces and moments must be considered, but also representativity of the deformation of the fastener whatever the loading is important for model predictivity.
Typically, Stellantis has moved from a semi-rigid representation using 1D elements to connect 2 parts to a 3D representation of the fastener itself. Advantage of this modeling is both a better representativity of the screw itself and to model connected part local deformation around the connection. Nevertheless, in the context of an explicit integration scheme, if the FE mesh is sufficiently fine to accurately capture the bolt geometry, mass scaling may become problematic, whereas using a coarser mesh will inevitably affect result precision. Moreover, mesh dependency in orthoradial and axial directions are particularly problematic for shear loading.
As LS-DYNA solver maturity on Iso Geometric Analysis is well established for shells, tested and validated by Stellantis on full scale models, it is natural to question whether 3D IGA modeling can be an efficient and precise solution for a better predictivity on bolt assemblies.
Starting with a pure qualitative study on a diameter 10mm screw assembling 2 solid parts this paper shows FE model status and how IGA can provide a promising answer. The discussion then turns to the M10 grade 10.9 for material and fracture calibration, using a generic model for 3D stress field dependency. Finally, next steps and challenges are introduced.

3 Qualitative study on M10 screw

3.1 FE modelling: Current status and issues

This paragraph refers to a model containing 2 steel parts assembled by a bolt made of high strength steel as presented on Fig.1:

- Top part thickness is 20mm and centered hole diameter is 11mm. Bottom part is 58mm thick and centered hole is the same as bolt (10mm).
- The bolt is assembled on bottom part with a tied contact, whereas only a segment-based contact (invoked using the SOFT=2 option in *CONTACT keyword in LS-DYNA) connects the bolt to the upper part.
- The bolt is pretensioned during 1st 3ms, then a displacement is imposed on top part either in Z direction for tension or in Y direction for shear loading.
- Fracture is permitted only in the bolt material, using the simplest fracture criterion with a constant ultimate plastic strain ε_f=12% irrespective of element stress type (triaxiality or Lode parameter).

This model can refer to 2 different mesh sizes variants and 4 variants concerning mesh positioning of the screw.
"Coarse" Mesh size variant is approximately 3 mm on external skin of bolt body, whereas it is about 1mm for "fine" variant.
Mesh position variants are in 2 dimensions: for each position variant a symbol will be used is used throughout the remainder of the document as depicted on Fig. 2.

1. Axial position versus contact plane between upper and bottom parts: either element nodes are aligned on contact plane (variants 1 and 2), or elements are centered on contact plane (variants 3 and 4). These configurations will be called "centered" or "aligned" hereafter.
2. Orthoradial position of the bolt body: in Y direction, either elements are parallel to the mesh of top part, or their nodes are centered on elements of upper part.

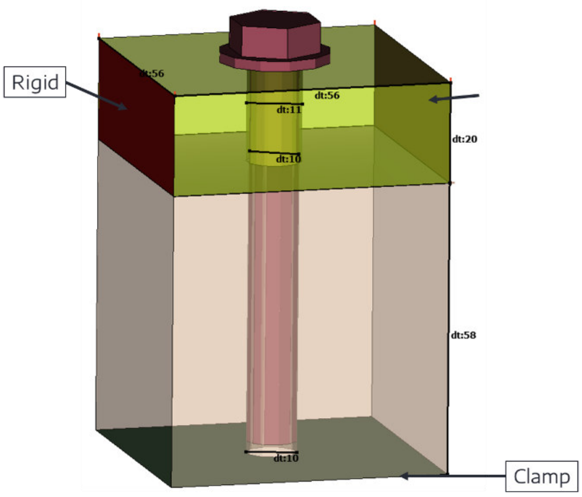


Fig.1: Functional model

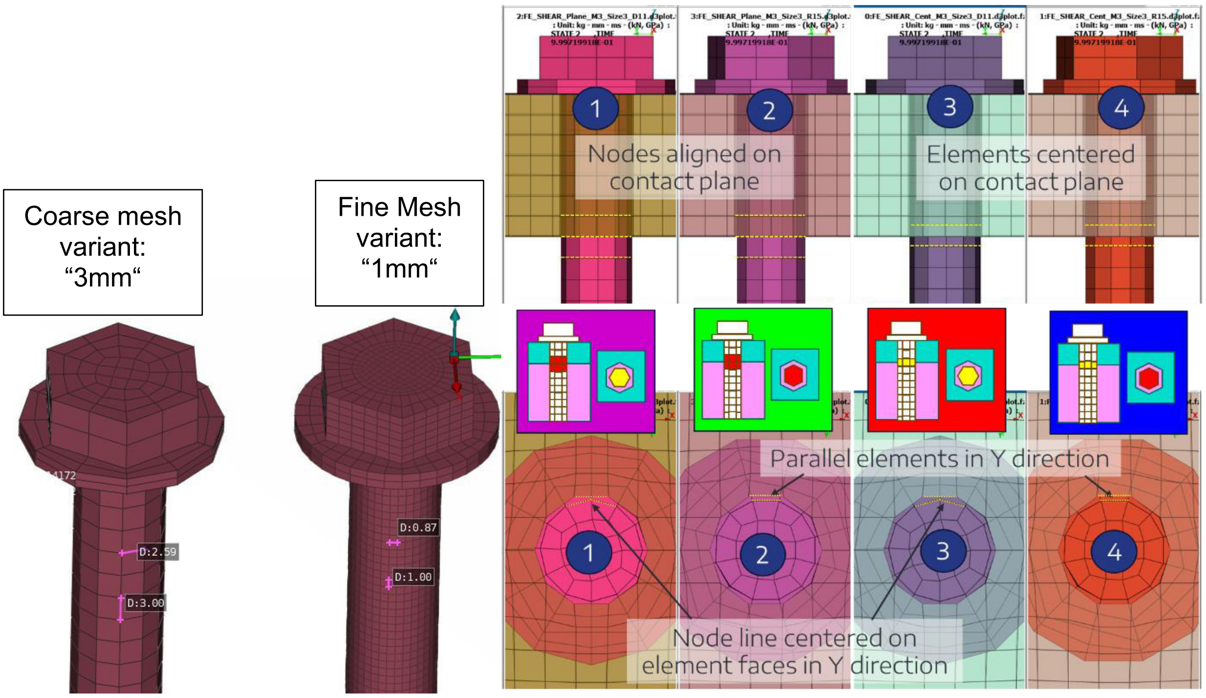


Fig.2: Mesh variants

3.1.1 *Tension mesh dependency*

The FE modeling of bolts exhibits a minor dependency on mesh position. Indeed, the location of maximum strain is only approximate, which leads to variations in necking behavior depending on the axial mesh configuration as shown on Fig 3. The meshes are identical in both models, with the only difference being z-coordinate of the nodes. Therefore, the maximum plastic strain is model-dependent. Nevertheless, maximum force is repeatable and if mesh is fine enough, maximum displacement before separation is accurately computed.

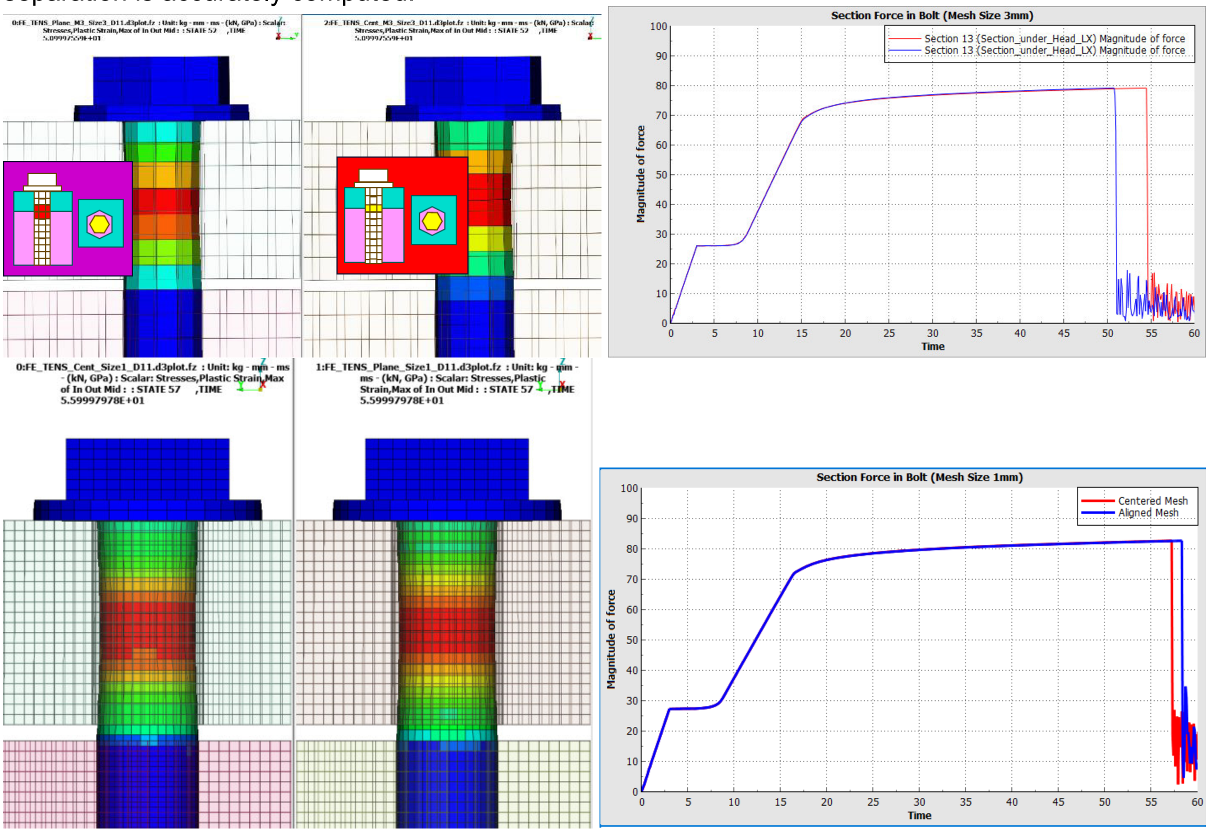


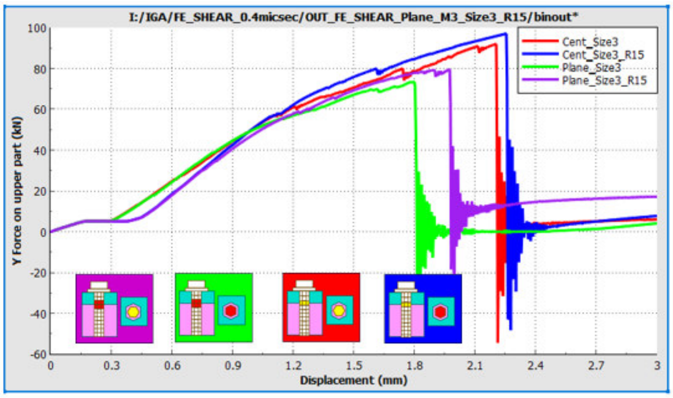
Fig.3: Axial mesh dependency in tension

3.1.2 Shear

Shear loading has been tested for both mesh size variants and for each 4 positioning variants.

- **<u>For 3mm mesh size</u>**, variation of deformation and stress state and separation force is very high:
  - Separation displacement can vary by 25% and forces by more than 30% between mesh positions (see Fig. 4)
  - Significant differences are observed in the plastic strain fields across all mesh positioning variants (see Fig. 5)
  - On eroded elements: triaxiality fields during plastic phase are completely different between all variants as shown on Fig. 6

  Therefore, developing a precise material model is of limited interest, and shear separation cannot be reliably predicted.



Axial	Orthoradial	Displacement		Force	
Aligned	Opposed	1,80 mm	Ref	73,54 kN	Ref
Aligned	Parallel	1,98 mm	+10%	79,54 kN	+8%
Centered	Opposed	2,20 mm	+22%	91,94 kN	+25%
Centered	Parallel	2,26 mm	+26%	97,04 kN	+32%

Fig.4: 3mm mesh: Force/Displacement curves

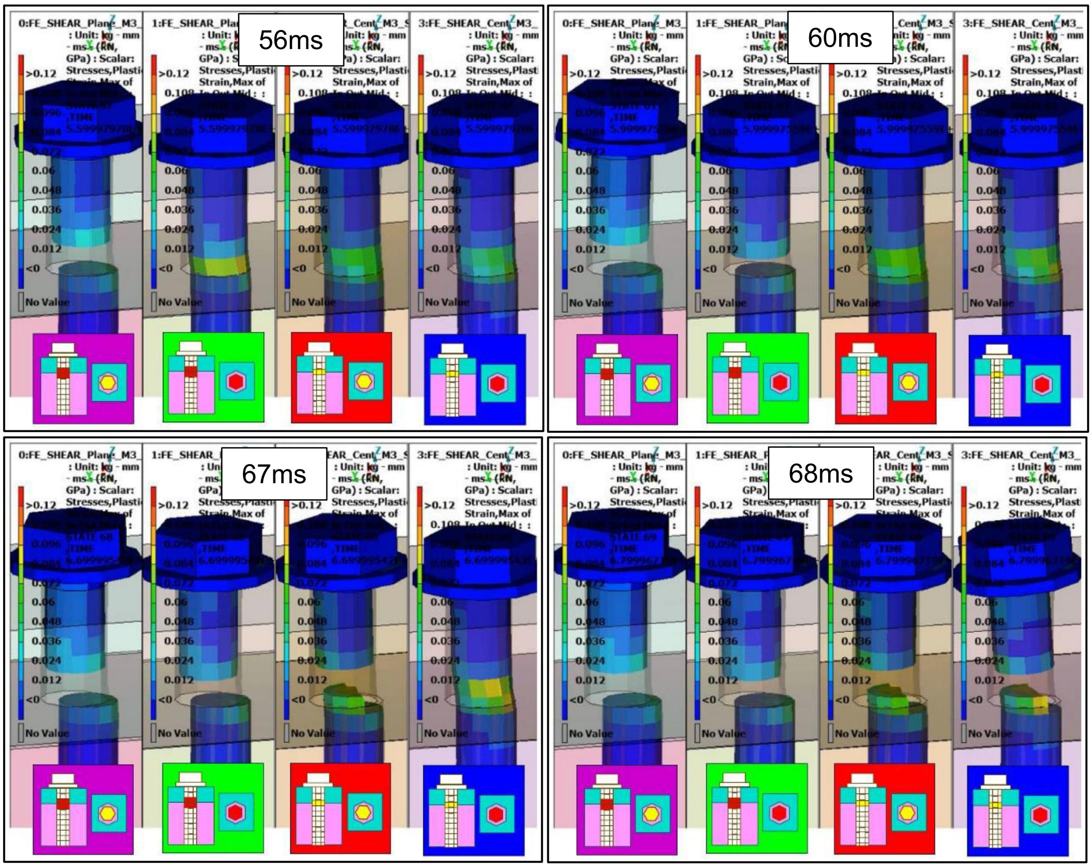


Fig.5: 3mm mesh: Plastic strains and 1st separation time for each mesh position

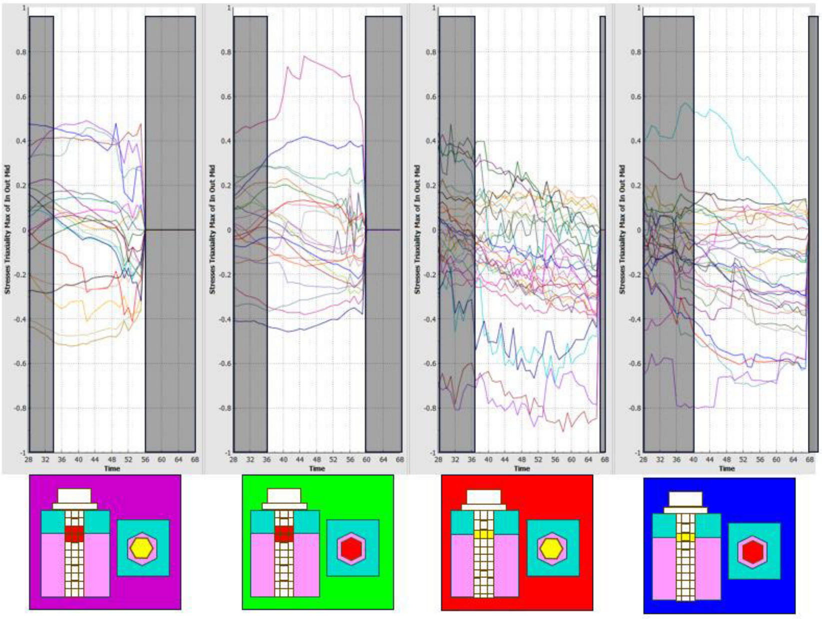
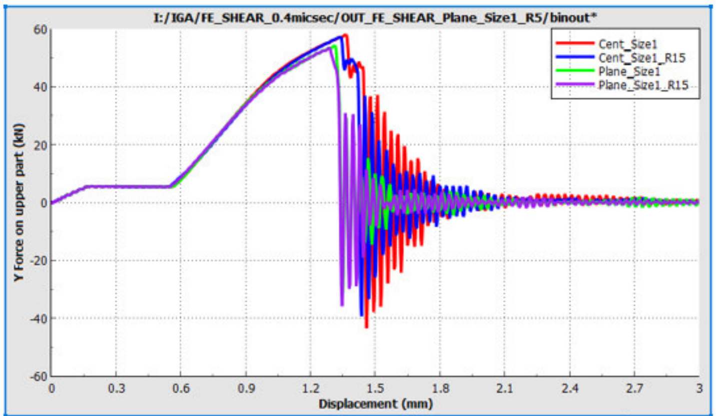


Fig.6: 3mm mesh: Measure of triaxiality on eroded elements

- **<u>For 1mm mesh size</u>**, variability of deformations and forces is acceptable, but stress state remains dependent on axial mesh position:
    - Separation forces and displacement variation is less than 8% (see Fig. 7)
    - Plastic strain fields are similar across all variants (see Fig. 8)
    - On eroded elements: triaxiality fields during plastic phase are not reproductible for axial mesh dependency as shown on Fig. 9

  Consequently, employing a precise material model is warranted. However, the definition of the fracture model depends on specifying the mesh position in the axial direction.



Axial	Orthoradial	Displacement		Force	
Aligned	Opposed	1,31 mm	Ref	54,23 kN	Ref
Aligned	Parallel	1,29 mm	- 2%	53,46 kN	- 1%
Centered	Opposed	1,37 mm	+5%	57,98 kN	+7%
Centered	Parallel	1,34 mm	+2%	57,20 kN	+5%

Fig.7: 1mm mesh: Force/Displacement curves

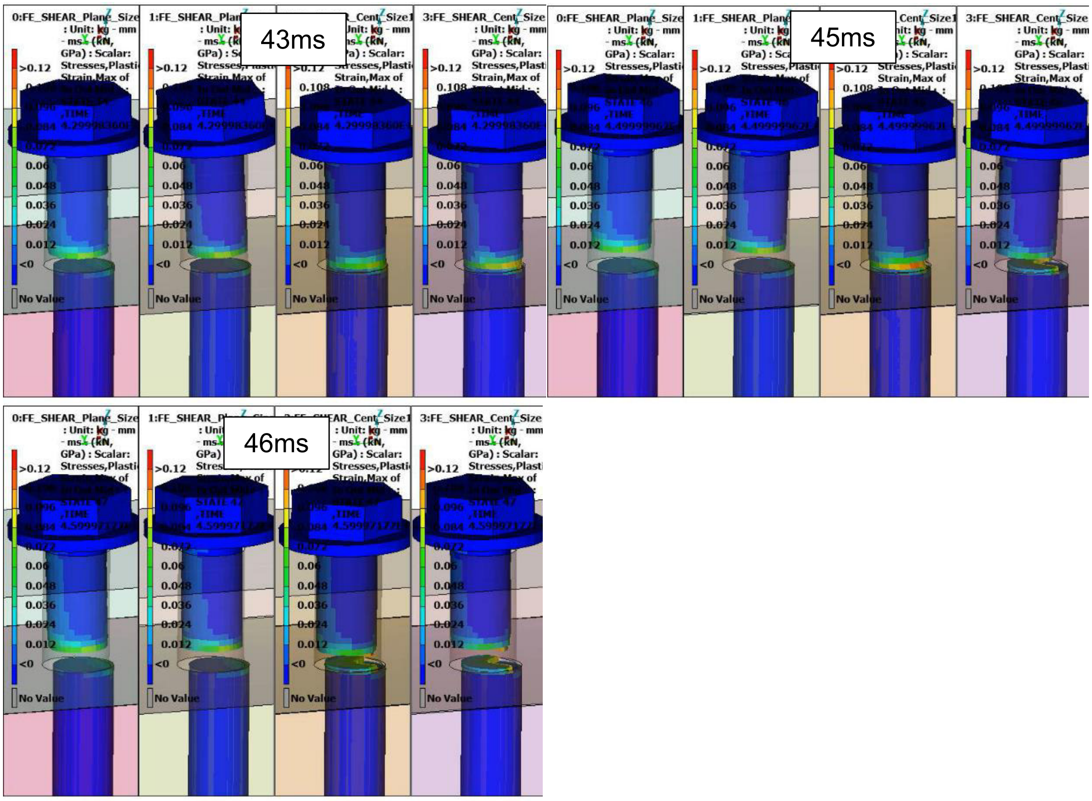


Fig.8: 1mm mesh: Plastic strains and 1st separation time for each mesh position

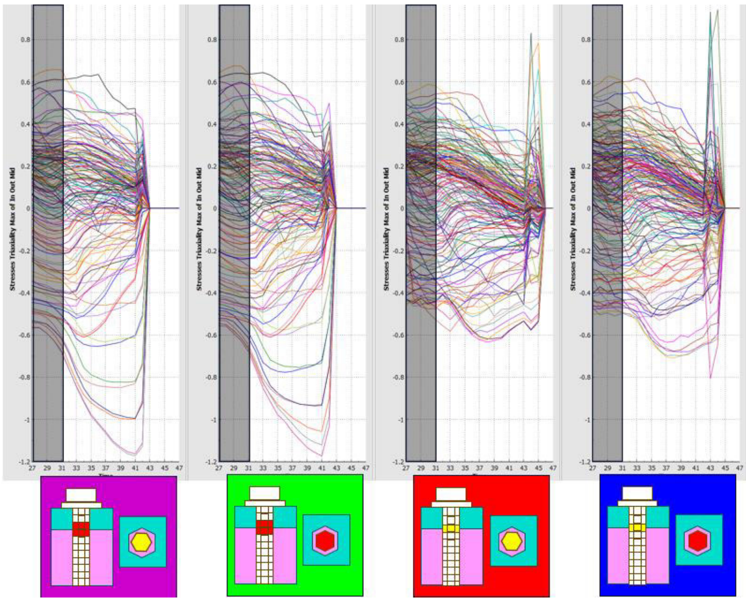


Fig.9: 1mm mesh: Measure of triaxiality on eroded elements

3.1.3 Conclusions:

Standard mesh size (3mm) does not allow a reproductible behavior of the screw for shear, whereas fine mesh allows a low difference in stiffnesses. Unfortunately, stress triaxiality field depends on axial mesh position of the bolt body. Then, a precise material model calibration will make sense for fine mesh size but fracture calibration using triaxiality and lode angle dependency is only reliable if strict rules are established for axial meshing, in order to avoid result dispersion under shear loading.
If this status is acceptable using a fine mesh size on component level, it cannot be generalized on full scale models; indeed, mass scaling is about 0.9kg per screw using Stellantis standard time step control which is not acceptable. In addition, lead time can be affected by respect of meshing rules for all bolt assemblies of a full-scale model.

3.2 IGA Status

For this part of the study, same model has been used with the addition of a 3D-IGA grid on bolt. Then FE mesh of the screw becomes an “interpolation mesh”, and material definition is associated to IGA part.
For all IGA models, IGA elements are quadratic. Interest of order 3 for this study was very limited.
Instead of mesh size dependency, IGA grid size dependency is considered (3mm and 1mm), and mesh dependency is replaced by grid location dependency. Same symbols as 3.1 paragraph are used as presented in Fig. 10.
In order to avoid any trouble related to result mapping, the interpolation mesh remains constant for this part of the study.

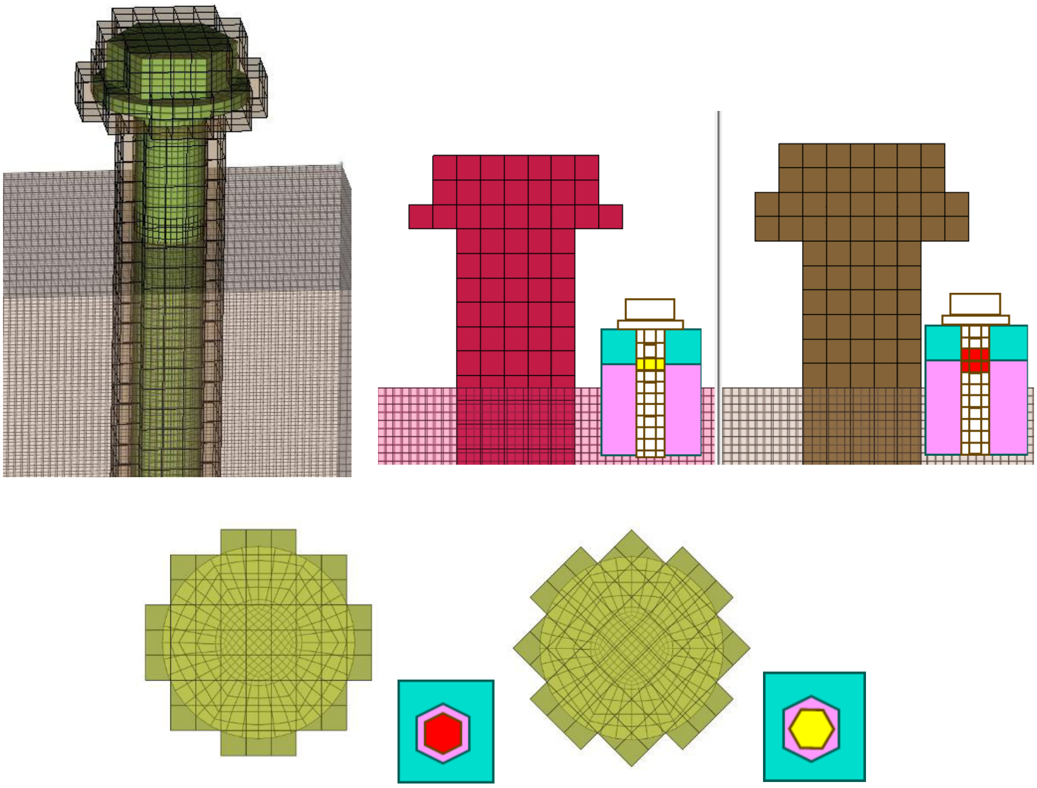


Fig.10: IGA Grid variants

3.2.1 Tension IGA grid dependency

In tension, IGA Grid position has no effect on forces and separation time. However, isovalues are notably different, probably due to the effect of result mapping.
Additionally, effect of grid size is very low on curve shapes; only time (⇔displacement) to separation differs between grid sizes

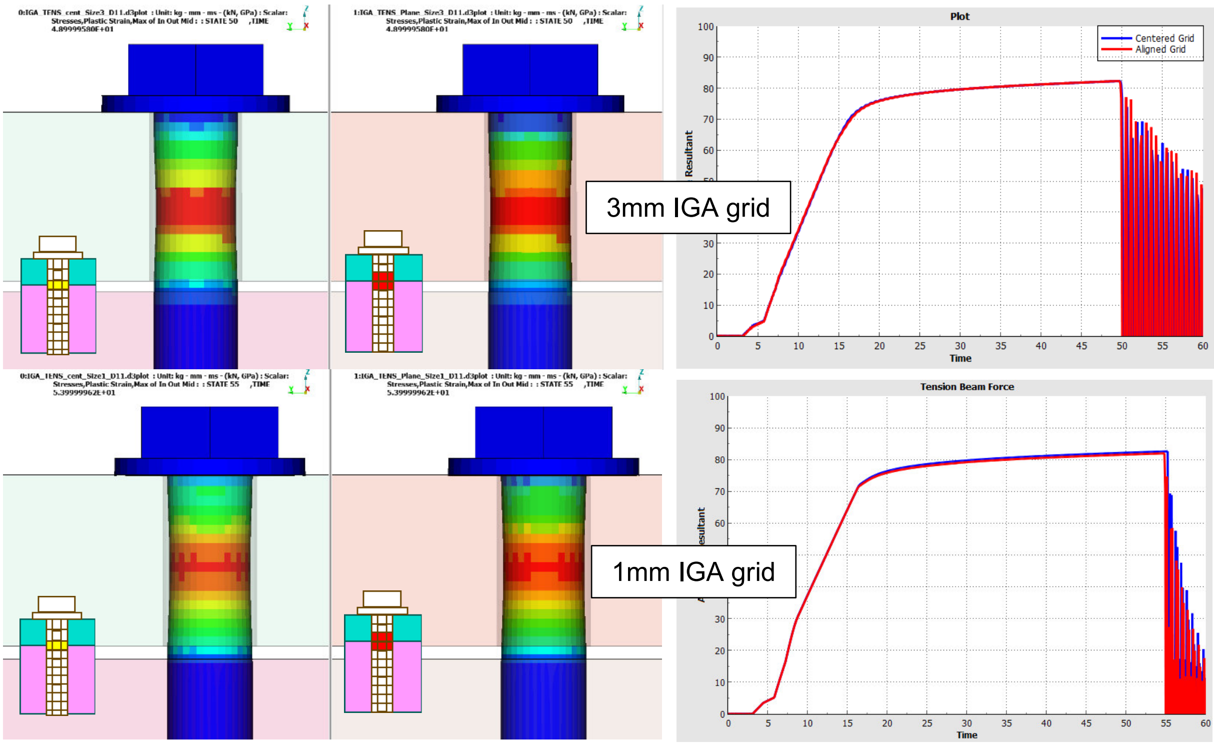


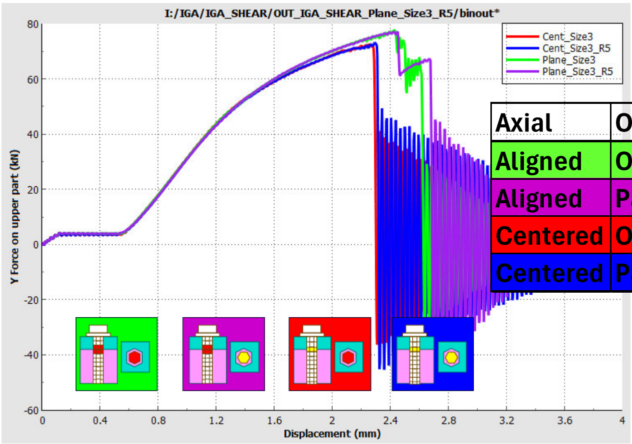
Fig.11: Axial grid position dependency in tension

3.2.2 Shear IGA Grid dependency

Following same approach as with mesh configurations, shear loading has been tested for both IGA grid size variants and for each 4 positioning variants.

- **<u>For 3mm IGA grid</u>**, variation of separation force is limited compared to FE:
  - Separation displacement can vary by 8% and forces by 7% between grid positions (Fig. 12); however, separation appears different depending on axial position of the grid.
  - Plastic strain fields differ noticeably between axial positioning variants (Fig. 13): Rather than performing any interpolation or extrapolation from the IGA integration points to the interpolation mesh, the mapping is carried out by assigning each point the value of its closest IGA integration point on the interpolation element. Then the result mapping from 3mm gids onto 1mm interpolation mesh can explain this difference.
  - For same reason, triaxiality fields observed during the plastic phase in eroded elements are totally different between variants, as shown on Fig. 14.

Consequently, it is currently impossible to determine whether IGA results on 3D scalar fields are repeatable when the IGA grid size is not comparable to the mesh size. Nevertheless, the grid size should be finer to get a better repeatability.



Axial	Orthoradial	Displacement		Force	
Aligned	Opposed	2,43 mm	Ref	77,68 kN	Ref
Aligned	Parallel	2,45 mm	+1%	77,14 kN	-1%
Centered	Opposed	2,26 mm	-7%	72,53 kN	-7%
Centered	Parallel	2,29 mm	-6%	73,16 kN	-6%

Fig.12: 3mm IGA: Force/Displacement curves

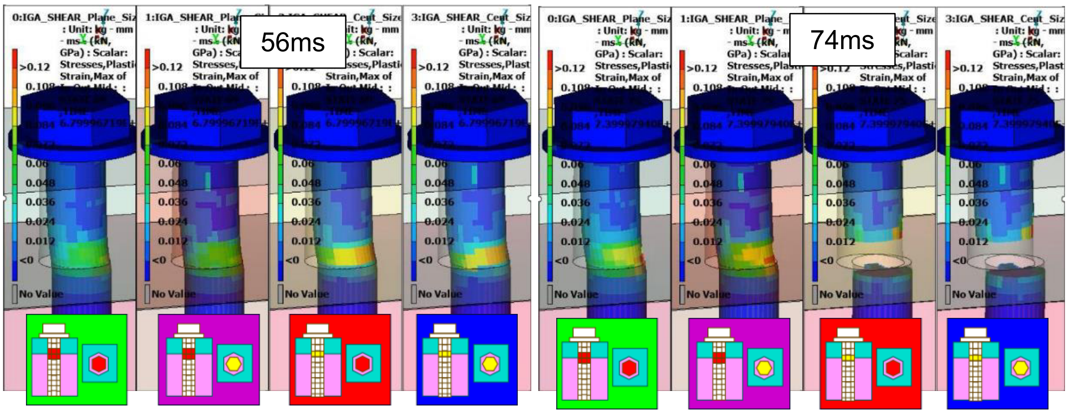


Fig.13: 3mm IGA: Plastic strains before separation time for each mesh position

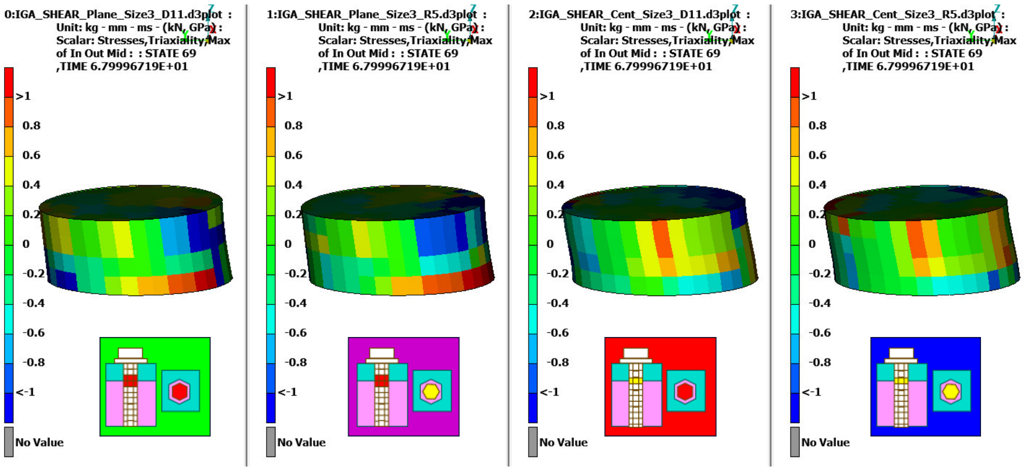
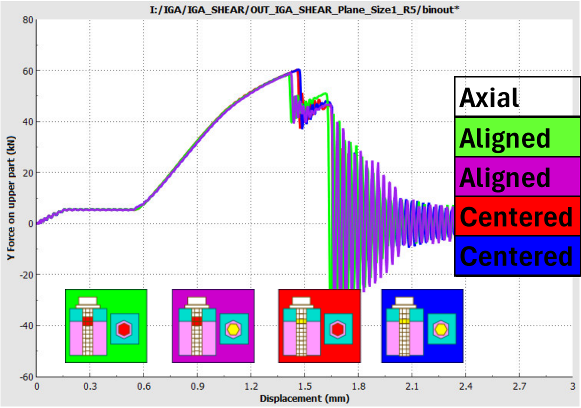


Fig.14: 3mm mesh: Stress triaxiality on eroded elements

- **<u>For 1mm grid size</u>**, variability of deformations and forces is very low, and 3D fields are very similar:
  - Separation forces and displacement variation is less than 4% (Fig. 15)
  - Both Plastic strain and triaxiality fields are looking quite similar (Fig. 16 & 17). Using same mesh size as IGA grid is much better, even if maybe mapping of results on interpolation mesh is not yet perfect.
  - Added mass is lower than equivalent FE mesh size (330g)

  Accordingly, a precise material model is meaningful, and the fracture model can be specified without reference to the IGA grid position.



Axial	Orthoradial	Displacement		Force	
Aligned	Parallel	1,41 mm	Ref	58,60 kN	Ref
Aligned	Opposed	1,42 mm	+1%	59,12 kN	+1%
Centered	Parallel	1,46 mm	+4%	60,28 kN	+3%
Centered	Opposed	1,47 mm	+4%	60,37 kN	+3%

Fig.15: 1mm IGA: Force/Displacement curves

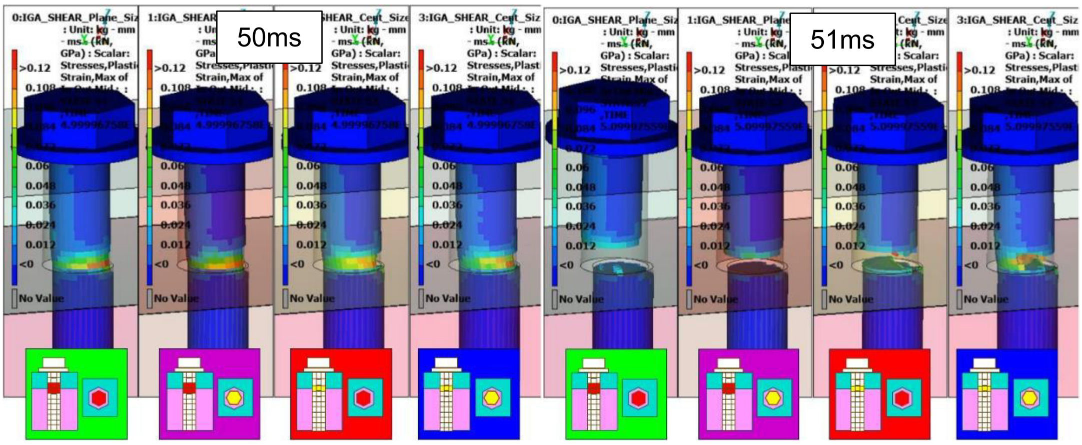


Fig.16: 1mm IGA: Plastic strains and 1st separation time for each mesh position

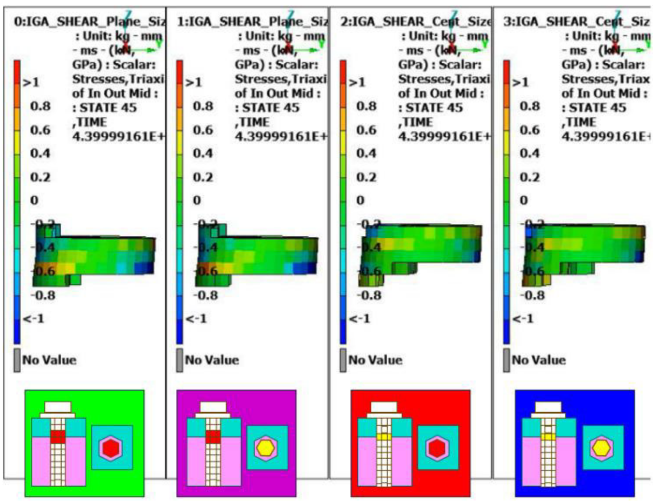


Fig.17: 1mm IGA: Stress triaxiality on eroded elements

3.2.3 Conclusion:

IGA demonstrates a lower mesh dependency than FE, although some dependency remains at a 3 mm grid size in axial direction. In addition, IGA mass scaling is lower than equivalent FE mesh size.
For coarse grids, certain isovalues may appear unexpected, likely due to approximations introduced during result mapping onto the interpolation mesh.
However, for finer grids, IGA results show near-complete independence from grid positioning. Both plastic strain distributions and triaxiality values remain consistent, reinforcing the robustness of the method.
This consistency highlights the relevance of precise material model calibration, without paying attention to the grid placement in IGA simulations.
Overall, IGA offers promising capabilities for accurately modeling the mechanical behavior and separation phenomena in bolted assemblies, with a high level of correlation.

4 Material and fracture calibration

4.1 Additional analysis on qualitative IGA model for shear test

4.1.1 IGA⇔FE comparison (1mm mesh/grid size)

A few interesting observations emerge from Fig. 18 and Fig. 19:

- F/D curve shapes are very similar between 1mm mesh size and IGA model.
- On IGA models, oscillations before separation are lower using IGA grid centered on connection plane.
- Separation occurs differently between IGA and FE model.
- Best fitting for FE is centered configuration.
- Stress triaxiality and the Lode parameter are well captured, exhibiting close agreement between the centered FE and centered IGA results.

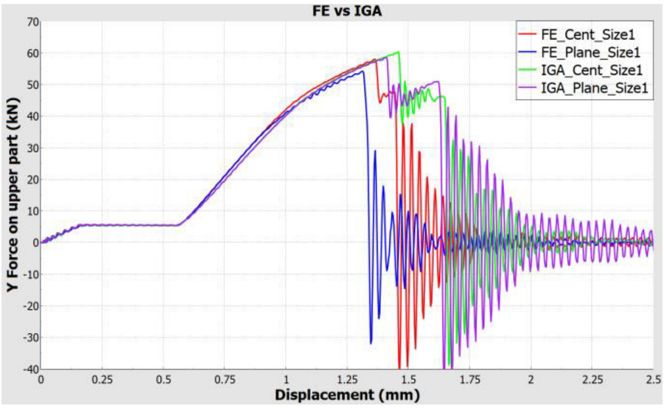


Fig.18: Force/displacement comparison between FE and IGA model

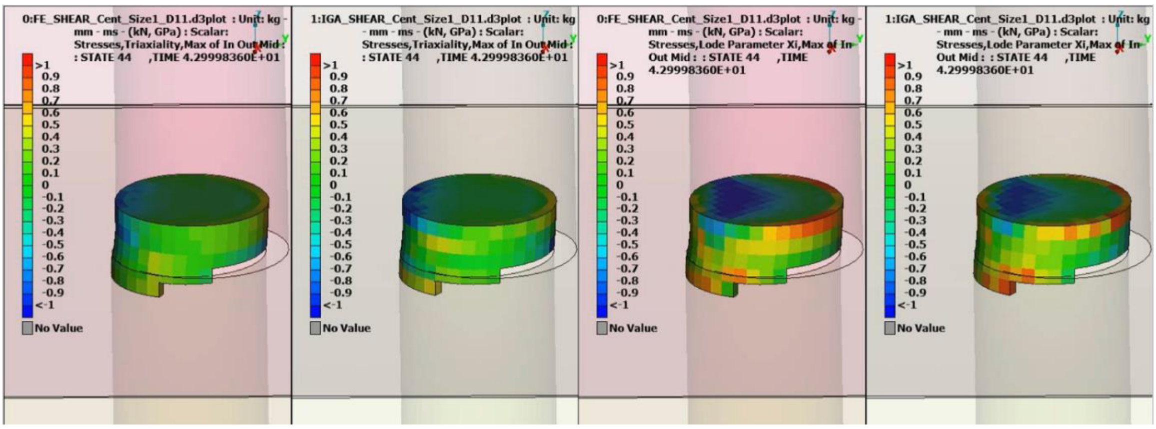


Fig.19: Triaxiality and Lode parameter for FE and IGA centered configuration

Consequently, for the remainder of the study, only the 'full centered' configuration is used, with both the IGA grid and the interpolation mesh centered on the contact plane.

4.2 Testing on M10 screws

4.2.1 Testing conditions

2 different testing conditions are considered on same test bench as shown on Fig.20:

- Upper part is made of steel and connected to the mobile cylinder by a revolute joint.
- Mobile cylinder can only move in Y direction in quasistatic conditions.
- Upper part is bolted on a clamped load cell in Y direction for tension test
- Upper part is bolted on the clamped loadcell in Z direction for shear test
- Chosen bolt is M10 Grade 10.9

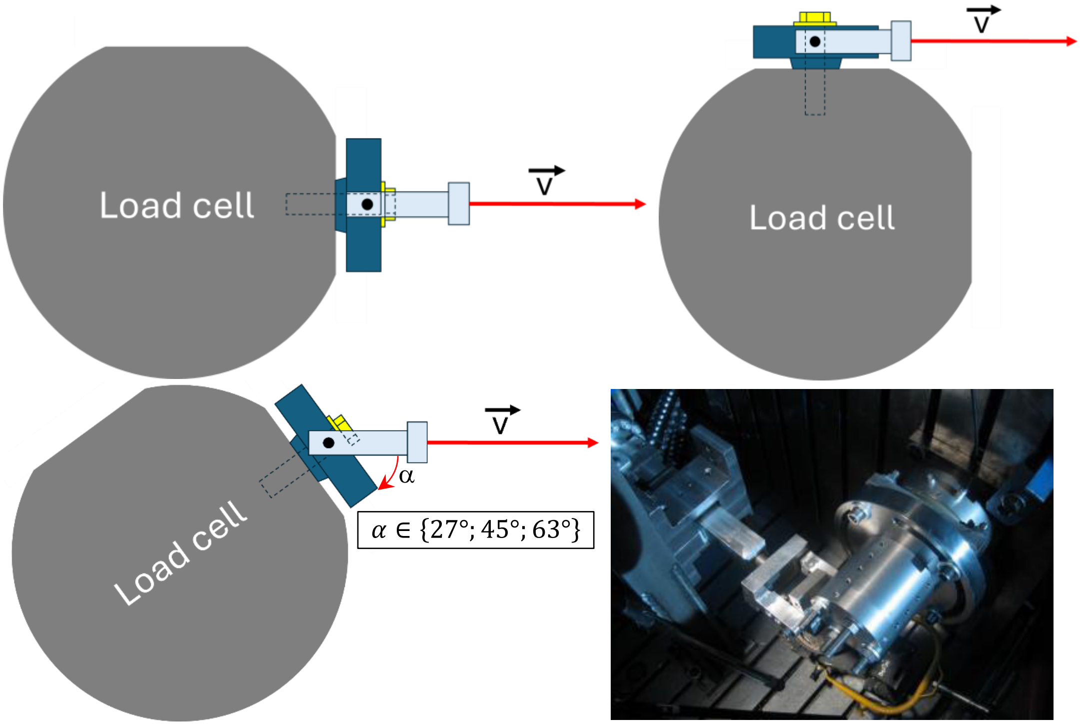


Fig.20: Testing condition

4.2.2 Testing results

As shown on Fig. 21, screw strength depends on loading angle. Except for shear, forces are quite repeatable.

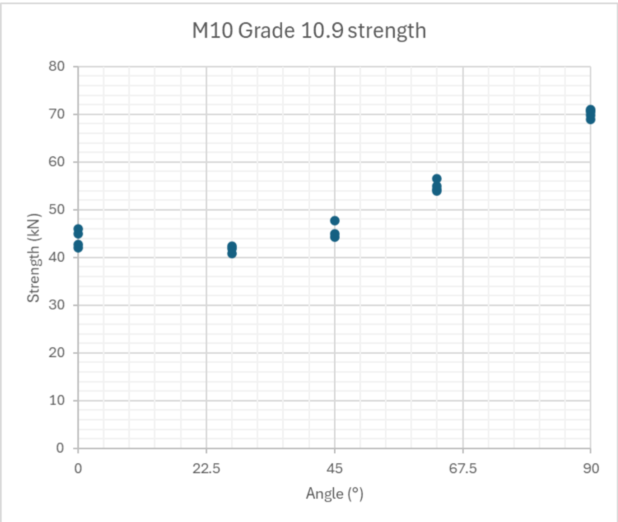


Fig.21: Axial / Transverse strength dependency

For CAE⇔test correlation, only 1 test is selected. Note that during this test campaign, displacement measurements showed significant variability between tests, probably due to a bad positioning/anchorage of laser sensor. Thus, only time-based curves can be considered. Therefore, only shape of curves can be compared between test and CAE. The expected curve shapes are shown on Fig. 22.

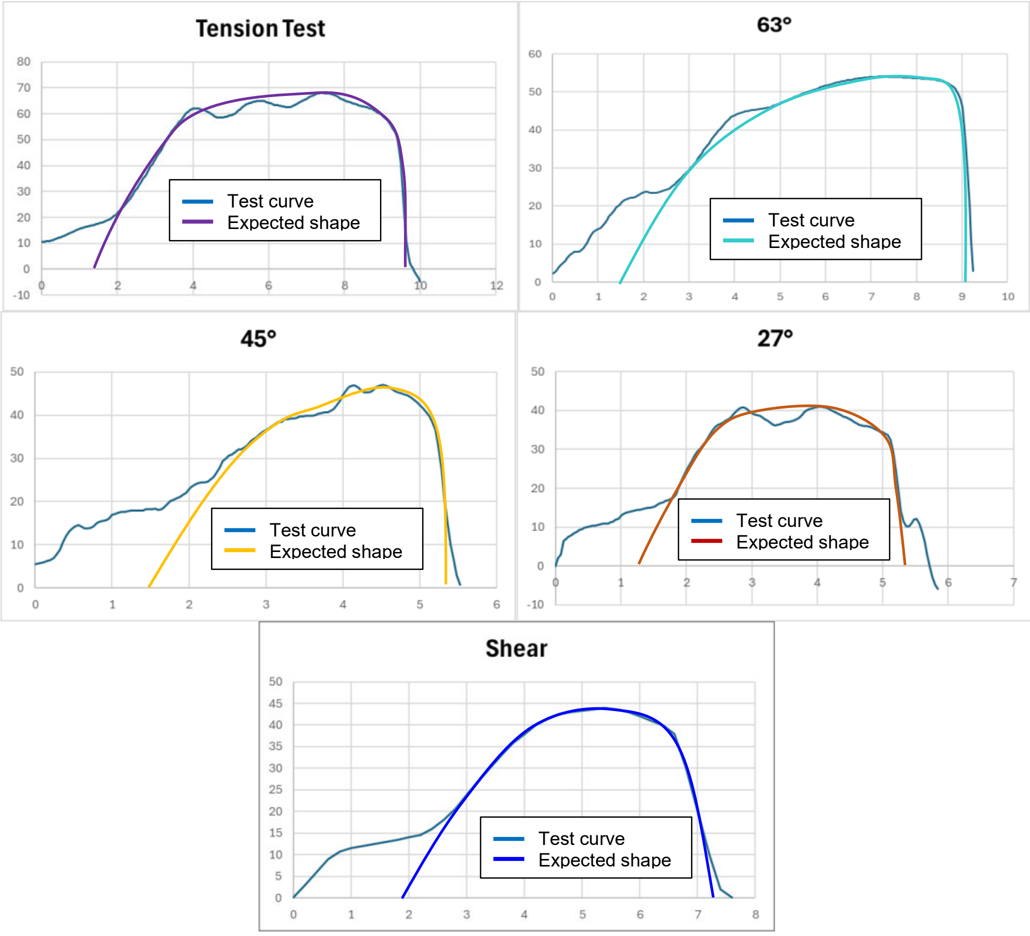


Fig.22: Reference test curves and shapes

4.3 Bolt properties

4.3.1 Bolt geometry

Even if bolt diameter is 10mm, its cross section is not πr^2 (about 78.5mm²) because of its 1.5mm thread. A more effective approach would be to exclude the threaded area from the section. A first approximation is to use 10-1.5=8.5mm to calculate cross section, giving 56.7mm². General value is slightly higher (58.0mm²) to consider the small part of the thread intersecting section plane. Nevertheless, a variation in the section of roughly 25-30% is substantial and must be taken into account.
Two different strategies can be adopted:

- For structural behavior, meshed diameter of the bolt should be reduced, but it would be problematic for contact. Indeed, an optional contact thickness (invoked using the OPTT option in *PART_CONTACT) must be defined but for shear a cantilever artificially affects element deformation (pushing upper part in Z+ direction)
- For contact, best accuracy is to consider external diameter of the screw. Consequence is an overestimation of both stiffness and strength ~25-30% in tension. Then material properties (Young modulus + Stress/Strain curves) should be scaled down to correct the material model.

For this study, choice is to use external shape of the screw and scale down material properties in order to use standard contact definition and avoid Z abnormal pushing of external elements deformed in shear.

4.3.2 Bolt material

As bolt grade is 10.9, standard material properties are estimated as follows:

- Standard material properties order is
  - Yield stress: ~900 N/mm²
  - Ultimate stress: ~1000 N/mm²
  - Fracture strain: ~9%
- Tightening torque is 60Nm, equivalent to a tensile preload of 41.1kN

Due to the fact bolt mesh is made of a cylinder with a mesh size of ~1mm, mesh cross section is 78.14mm² whereas bolt cross section should be 58mm² as mentioned in previous paragraph.
Then, for this study, mechanical properties should be scaled by 0.742 except material density.

Material calibration comes directly from tensile test correlation in association to a damage related stress fadeout (referred by the ECRIT and FADEXP parameters) in the GISSMO damage model considering a Young modulus of 156GPa.

4.3.3 Fracture model

From Jie Li [1], fracture model can be described using a generic equation:

$$\bar{\varepsilon}_f^P = C_3\left(\frac{\sqrt{\bar{L}^2+3}}{2}\right)^{C_1}\left[\frac{1}{1+C}\left(\bar{\eta}+\frac{3-\bar{L}}{3\sqrt{\bar{L}^2+3}}+C\right)\right]^{-C_2}$$

Fracture model calibration is based on identification of 4 parameters C, C_1, C_2 and C_3. For M10 Grade 10.9 fracture criteria dependency is shown on Fig. 23:

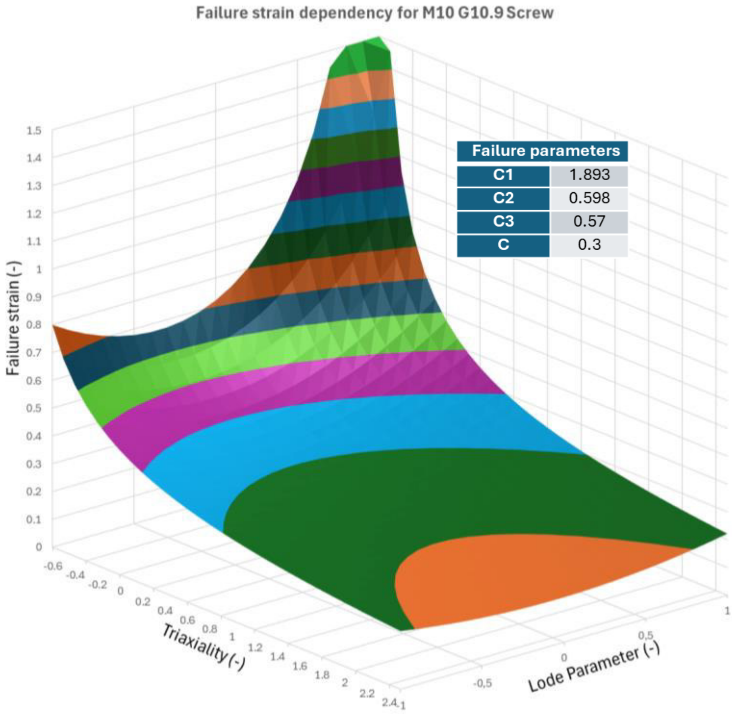


Fig.23: fracture parameters

5 Final results

As shown on Fig. 24, using default fracture parameters from Jie Li paper [1], IGA model can predict test separation forces and curve shapes. These 2 observations confirm that the behavior of the IGA modeling of the screw is well represented.

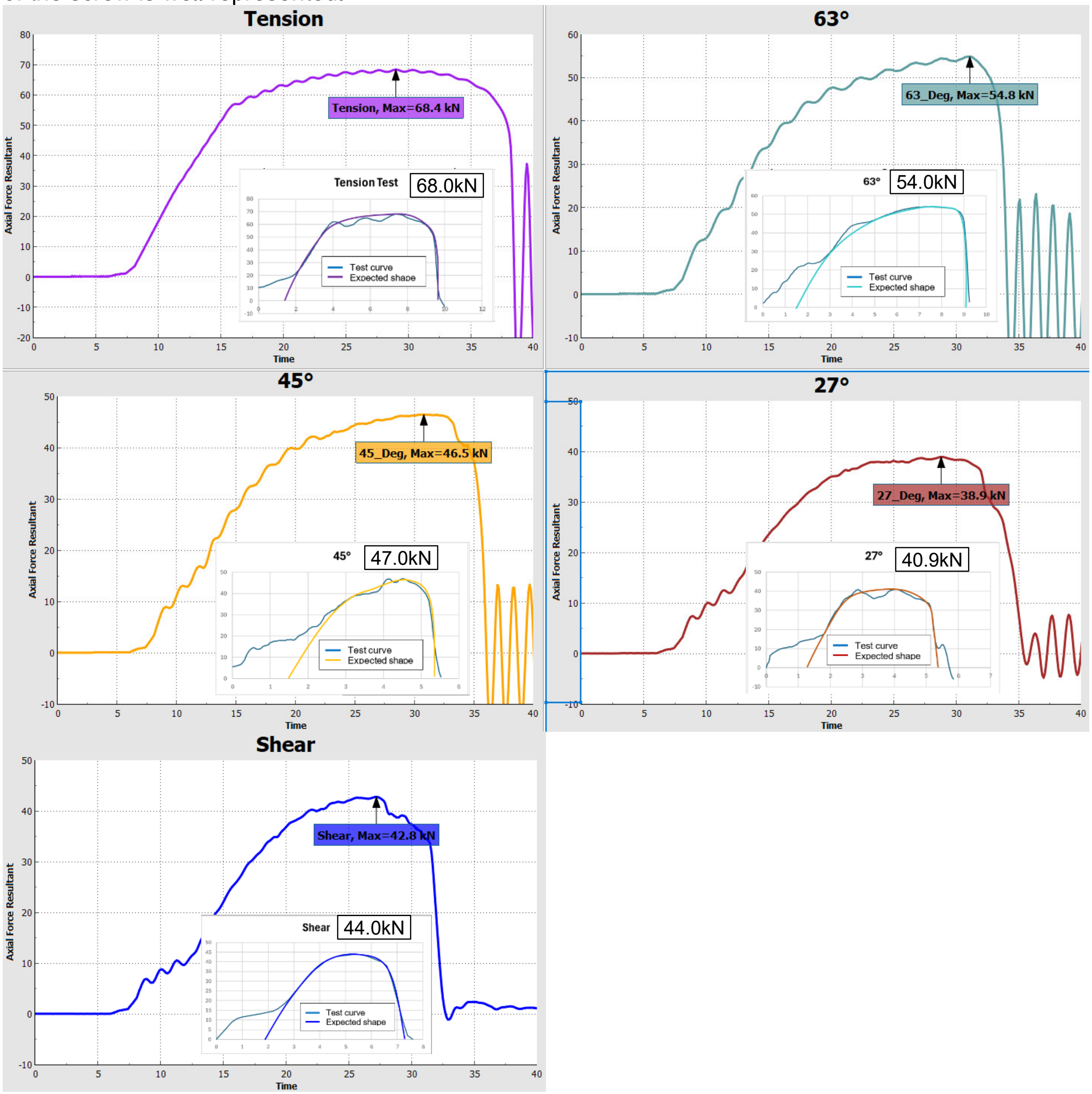


Fig.24: Force/time curves

6 Summary

IGA technique is very promising for bolt modeling.
First, a quasi-perfect IGA Grid independency could be demonstrated, even for pure shear loading, which is not the case for standard FE. Wherever connection plan will be, whatever bolt orientation and interpolation mesh position, bolt strength and behavior will remain same.
Second, IGA necessary grid size can be coarser as FE mesh size for same accuracy.
Third, mass scaling is much lower than standard FE for same time step.
In addition, FE material calibration can be reused. For fracture calibration, only regularization will differ; triaxiality and Lode parameter dependencies can remain consistent with those used in FE models.
However, this solution for 3D parts is not yet fully mature in LS-DYNA R16, especially cross sections can give abnormal results, and 3D result mapping on interpolation mesh is still looking unperfect. These issues should be fixed very soon.
We look forward to future LS-Dyna developments that will enable direct work on 3D geometric entities, allowing better alignment with CAD details.

7 Literature

[1] Jie Li, Haohui Xin, Jos´e A.F.O. Correia, Filippo Berto, Bingzhen Zhao,Yanwei Bo, Milan Veljkovic: Mesh size effects on fracture locus of high strength bolts: A mesoscale critical equivalent plastic strain (MCEPS) approach, Engineering Failure Analysis 138 (2022)

[2] LS-DYNA Keyword User's Manual R16_DRAFT_Vol_I.pdf & R16_DRAFT_Vol_II.pdf