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Threated inserts pull-through behaviour in carbon-epoxy thick laminates

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Abstract

Aim of this work, is the experimental assessment of the mechanical behaviour of threaded inserts, commonly used in racing cars. Tests have been performed, both in tension and in torsion, as a function of the installation technique in composite materials. Different type of inserts have been considered to evaluate the influence of materials on the strength of the inserts. From results has been proved that the installation technique influences very little the pull through strength, whilst it mostly affects the torsion strength. In particular, the failure torque is heavily influenced whether a bonding adhesive is used or not during the insert installation. Numerical models have been also made to simulate the inserts pull-through, using the commercial code LS-Dyna®, an explicit finite element code especially used in crashworthy problems. Due to the thick composite structure, a thick shell numerical laminate has been modelled. The plies have been tied each other with a failure contact model. Numerical results show a good correlation with experimental data both in force-displacement curve and in material local damage.

Keywords: Carbon fibre, Thick laminate, Finite element analysis, Threaded insert, Pull-through test.

1. Introduction

Nowadays composite materials find a wide application in technologically advanced fields like aeronautical, naval and automotive industry, for which lightweight is pursued to obtain high dynamic performances and low fuel consumption. Therefore, the complexity of structures requires a high number of junctions. In most cases, joints cannot be realized by adhesive bonding or welding to create a continuous junction. Indeed, due to the possible different nature of the parts to be connect or due to the need of disassembly and inspect the structures, discontinuous junctions are sometimes required.

Few research works have been done in the last years on threated inserts and pull-through tests. Among them, Adam et al. in [1] presented an experimental-numerical investigation on pull-through test of fasteners in laminates. From results, a good correlation between models and test data has been obtained in terms of load curves and damage prediction. Catalanotti et al. in [2] proposed a numerical-experimental study of failure modes in glass fiber reinforced plastic composite due to pull-through tests as a function of the resin type. A similar investigation has been proposed by Elder et al. in [3] but referring to carbon fiber epoxy matrix composite material.

The possibility to realize discontinued single sided junctions using screws is one of the issues related to composite materials structures. In fact, to directly hole and thread a fibrous reinforced composite material, with the aim of fasten screws in it, it can cause local material damages, reducing structural integrity. For these reasons, threaded metal inserts are widely used. The most common types used in automotive fields are Keensert®,

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Kobsert® and Time-sert®, see Fig. 1. These inserts, once installed, provide a metal threaded hole, which guarantee a longer life of the junction.

As an example in figure 2 is visible a racing car frame, where threaded inserts are largely used to create one sided junctions on sandwich panels. In similar cases, inserts are fundamental to have an easy and fast way to disassemble the junction.

The downside is that inserts installation is expensive in terms of time and costs. From the state of the art, the following steps are required:

- Milling of a threaded hole, in which the insert will be installed. The usual tapping tools are not used in order to avoid material damage. Figure 3 shows the different threading result of a M8 threaded hole in a 30mm thick carbon fibre laminate.
- Inserts sandblasting to prepare the surface for bonding
- Application of a bi-component structural adhesive
- Proper installation of the insert inside the threaded hole
- Adhesive polymerization at controlled temperature.

Manufacturers, that use composite materials, pay close attention when choosing and installing inserts and each acts based on its own know-how. For this reason, literature has shown a lack of knowledge about both the insert strength and the influence that installation steps have on it

Aim of this work is the experimental investigation of the mechanical behaviour of the mentioned inserts, installed in carbon/epoxy thick laminates, to better understand the failure mechanisms and the influence of the installation steps on strength. A detailed finite element model, capable of simulating the damage phenomena inside the composite material, has also been developed to compare experimental and numerical results.

2. Methodology

2.1. Experimental tests

To evaluate the strength of the inserts, an experimental campaign of pull-through and torsion tests have been done. The most commonly used insert the Keensert® M5, installed as the state of the art prescribes, has been taken as a reference. The variables of the experimental tests have been:

- Installation procedure: some installation steps has been changed or avoided, e.g. the thread had been tapped instead of milled, the sandblasting or the adhesive bonding had been avoided and , for Keensert® only, the locking keys are used or not (Fig.4).
- Insert size: M5, M6, M8 inserts
- Insert type: Keensert®, Kobsert® and Time-sert®

The material used for the laminate layup is a T300 carbon fibre reinforced plastic composite material, with epoxy resin. Both plain weave and 2x2 twill have been tested. The laminates were manufactured using a quasi-isotropic layup. Keenserts® M5 have been tested both on plain weave specimens and on 2x2 twill ones. Instead, the other inserts have been tested only on plain weave specimens. To apply the load, bolts of class 12.9, according to [5], have been used.

An MTS 810 testing machine has been used for pull-through tests. The equipment used is shown in Fig. 5. Bolts have been pulled under displacement control at a constant speed of 2 mm/min.

For torsion tests, specimens have been locked in a bench clamp and the torque has been applied using a dynamometric torque wrench according to Fig.6.

The load has been transferred to inserts using bolts of class 12.9. Starting from a minimum of 1Nm, the torque has been increased iteratively until failure (see Fig.7). Due to the test method, it has been impossible to measure the bolt, or insert, rotation.

2.2. Numerical model

The possibility of simulating the damage phenomena through a finite element model has been investigated. Aim of this numerical investigation is of the evaluation of the force-displacement curve and the reproduction of the damage inside the composite due to different loading conditions. Inserts of type Keensert® M5, M6 and M8 have been taken as references. The simulations have been performed using the commercial explicit finite element code LS-Dyna.

2.2.1. Model feature

In literature, some works concerning numerical simulation of fasteners pull-through failure in composite materials can be found [1-3, 5, 7], but none of them on threaded inserts. Due to the local nature of the failure phenomena, the basic idea has been to model in details the area surrounding the insert, including also the crests of the thread. The system to be simulated required a model capable to compute tridimensional stress states and to reproduce delamination. Thus, a ply-by-ply modeling approach has been used. Each ply has been modeled with a layer of solid elements, bonded together with a proper contact algorithm to simulate delamination. LS-Dyna supply a wide range of combination of element and material types to model composite materials [8-14].

The element type used is a multilayered solid element called thick shell (*TSHELL), an eight nodes shell element able to capture tridimensional stresses. The choice of this type of element was leaded by the need to have acceptable CPU times with respect to the usage of solid elements.

Also the material model had to be able to capture the damage of the material on the basis of a three-dimensional stress based failure criterion. Thus the *MAT_COMPOSITE_FAILURE_SOLID_MODEL (*MAT_59) has been used. A good description on how it works is given in [13].

LS-Dyna® offers different methods to model delamination. Due to the negligible thickness of the bonding layers between each ply of a laminate, the bonding has been modeled with an *AUTOMATIC_ONE_WAY_SURFACE_TO_SURFACE_TIEBREAK contact algorithm. The failure OPTION=6 has been chosen. For this option the coincident nodes of the plies are tied together, inhibiting relative motions, until a fracture criterion is reached. This criterion is based on normal and shear inter-laminar strengths (NFLS and SFLS respectively) and it is expressed as:

$$\left(\frac{\sigma_n}{NFLS}\right)^2 + \left(\frac{\sigma_s}{SFLS}\right)^2 \geq 1 \quad (1)$$

where σ_n e σ_s are the normal and the shear nodal stresses respectively. When the criterion is satisfied the contact stress is linearly reduced to zero in a given number of time steps.

The modeling of the insert was made with solid elements. Due to the absence of plastic deformation of the inserts after experimental tests, it has been modeled with the elastic material model *MAT_ELASTIC (001).

The interaction between the insert and the laminate has been modeled with an *AUTOMATIC_ONE_WAY_SURFACE_TO_SURFACE_TIEBREAK as well. In this way it has been possible to take into account the effects of the adhesive bonding between the insert and the laminate.

Not all the parameters required to characterize materials and contacts were available in literature. The out of plane elastic properties were derived by an analytical model called MESOTEX, based on a micromechanics approach [15]. Through-thickness strength properties were taken from a work of experimental investigation of thick laminates [16]. Delamination and adhesive bonding resistances were extrapolated from material and adhesive datasheets respectively. Materials main constants are reported in Table 1.

2.2.2. Model geometry

Neglecting the helix angle of the thread, the geometry shows two planes of symmetry. The material is orthotropic and the layup of the laminae is quasi-isotropic as well. These circumstances allowed a one-quarter modeling of the entire system to save CPU time, see Fig.8.

The thread pitch was 1,25mm thick, so each layer has been created with a thick of 0,25mm in order to model each crest of the thread with an entire number of layers. Elements have been modeled to have a width versus height ratio close to one, in this way, 634 elements per layer have been obtained.

The real specimen is subject to nonlinear constraints. In facts, due to the equipment design, the laminate was just leaned to the fixture while the test was running. To model this kind of constraint, an elastic solid block has been created with the same material model and elements type of the insert. The block-laminate interface has been modeled with a one-way contact algorithm. Symmetry constraints have been added to the model to reproduce the effect of the non-modeled part of the structure.

To better catch the system behavior, the more deformable parts of the equipment have been added to the model. Thus the pulling bolt and the washers used to set up the test were modeled, see Fig. 9.

The entire model is shown in Fig. 10. The screw and the insert have been tied together with a *CONSTRAINED_NODAL_RIGID_BODY algorithm, that constrains the coincident nodes to form a rigid body.

The bolt and the washers have been modeled using an elastic-plastic material model (*MAT_PIECEWISE_LINEAR_PLASTICITY). Material parameters are the minimum guaranteed by ISO standard for the used fasteners classes, see Table 2 and Table 3.

The load has been applied as a constant velocity law of 1 m/s. Following the same guidelines, the models for the Keensert® M6 and M8 have been created.

2.2.3. Model calibration

Once the models have been created, a calibration process was necessary. From the preliminary investigations it has been observed that, when the through-the-thickness tensile strength were reached, elements deletion were activated instead of nodes bond breakage. Thus delamination did not work properly. To avoid this phenomenon, which brought to prevent tangential frictional forces between the laminae, material failure in the normal direction has been inhibited.

When the insert is pulled through the laminate, the joint failure is due to the rupture at the base of the crests of the thread. Thus, the calibration of the model has been carried out concerning the out of plane shear strengths of the material and the inter-laminar strengths between the plies. The gain of correlation between numerical and experimental results has been pursued increasing the failure load up to the experimental one and changing the force-displacement curve shape in order to obtain the load plateau shown by the experimental curves.

3. Results

3.1. Experimental results

3.1.1. Pull-through tests

In most cases, the failure was due to insert extraction, caused by thread rupture. Only Keensert® M6 and Kobsert® M6 and M8 failures were due to bolt rupture, see Fig. 11.

Fig. 12 shows the typical force versus displacement behaviour according to ASTM D7332/D7332M [17], in which critical loads are defined. Among them, the most important are:

- Failure force: the maximum force magnitude achieved prior to the first significant (greater than 10%) drop in applied force
- Maximum force: the maximum force carried by test specimen during the test

Multiple experiments have been done in order to verify the repeatability of the tests. Results on Keensert® M5, taken as a point of reference, are shown in Fig. 13. The curve doesn't increase as the displacement increases after a limit force value. This fact suggests a progressive material damage, due to local delamination. This behaviour is also visible for other installation modes, see Fig. 14.

Plain weave specimens, see Fig. 7 (a) and (b), don't show a clearly identifiable failure force. In some cases, the maximum force had to be considered as the failure one. On the contrary, 2x2 twill specimens, see Fig. 14 (c) and (d), show a more marked drop in force, after a first peak, that defines the failure force.

In Fig. 15 the results from the test of different insert type and size are shown. As expected, the pull-through strength grows up with insert size.

In very few cases, delamination grew up through the laminate and reached the specimen surface. To investigate local delamination and better evaluate the failure, some specimens have been sectioned and a dye penetrant inspection (DPI) has been done. Delamination is clearly visible in correspondence with the insert bottom, see Fig. 16. The dark areas between delamination planes indicate porosity, i.e. matrix damage. This is supposed to be due to the inter-lamina and intra-lamina shear failure of the matrix and the consequent growth of micro cracks. Compression damage is excluded because under the equipment contact area, where compression is the major component, the dye did not penetrate the specimen. For what concerns those inserts, which brought to bolt failure, the typical section inspected with dye penetrant is shown in Fig. 16.

3.1.2. Torsion tests

Torsion tests were affected by a large dispersion, but have brought interesting results. Indeed, the failure of the junction is always due to bolt rupture, see Fig. 17, except in those cases in which adhesive has not been used to bond the insert. In these last tests, inserts began to rotate at very low torques.

3.1.3. Experimental results: final observations

Experimental results can be summarized in few observations:

- The maximum pull-through force is not appreciably influenced by the installation mode
 - In torsion tests, the only variant that penalizes the junction resistance is the absence of adhesive bonding.
- In such cases, torque resistance is low enough not able to prevent any bolt tightening.

On these observations, time expensive operations like sandblasting and thread milling seems not to be necessary and can be omitted, while adhesive bonding is mandatory. However, additional investigations are required to verify the necessity of adhesive bonding, especially fatigue tests.

3.2. Numerical results

Numerical results, compared to experimental ones, are shown in Fig. 18 and Fig. 19.

It is necessary to remind that:

- Material parameters do not come from experimental characterization. Thus, the numeric curve has been compared to all the experimental ones.
- The differences in displacement between numerical and experimental curves are related to the deformation of those elements that have not been modeled, such as backlashes and friction between components and their deformation. The model of the entire fixture has been avoided due to the large number of parts and their influence in real tests cannot be defined.

As visible in Fig. 18 and Fig. 19, numerical and experimental curves have the same trend and show a quite good correlation. Table 4 reports the maximum loads reached in simulations and the average values of the experimental tests.

Having regard to the dispersion of experimental results, the differences with numerical results are small.

The first part of the numerical curves results shows some drops in force. This is due to the raw delamination model used. The damage of the material seems to be similar to the real one and the area around the hole has a truncated cone shape, see Fig. 20.

To verify the displacement of the insert, a comparison between the section of the damaged specimen and the numerical one has been done, see Fig. 21. As a result, a similar behaviour has been obtained.

4. Conclusions

Different inserts, in size and type, installed in thick carbon/epoxy laminates have been characterized in a pull-through test campaign and a numerical model of the test has been done.

From experimental tests, it was shown that the insert installation mode has a very little influence on the maximum pull-through strength of the joint. Only torsion testing showed a strong penalization in strength, when adhesive bonding is not used. For this reason time expensive procedures, as sandblasting and thread milling, turned out to be not essential, while adhesive bonding is fundamental. Another interesting result concerns the maximum and failure loads reached by junctions. The force versus displacement curve shape depends on the material used as a whole (set of a matrix and a reinforcement). The thread strength, and so the maximum load, is caused by the matrix and not to the reinforcement. Referring to the failure, even if the junction failure is due

to the rupture of the bolt, the material around the hole results to be damaged and it is not guaranteed it bears high loads again.

Numerical models are considered to be satisfying, even if they can be improved. The damage of the material has been reproduced and the same has been done with the maximum load, with a quite good approximation. In spite of the global differences between experimental and numerical force versus displacement curves, the model simulate properly the displacement of the insert. Thus, the model can be considered as acceptable.

Due to the approximations done during the creation of the model, this work can be considered as a first approach to the problem. A better numerical model could be obtained starting from a good material characterization, especially for composite.

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Table 1: Parameters of T300 carbon fibre reinforced composite material with epoxy resin matrix.

Parameter	Value	
Density	1,48E-09	tonn/mm ³
Longitudinal Young modulus	5,61E+04	MPa
Transverse Young modulus	5,61E+04	MPa
Normal Young modulus	9950	MPa
Poisson's ratio <i>ab</i>	0,04	-
Shear modulus <i>ab</i>	4700	MPa
Shear strength <i>ab</i>	117	MPa
Longitudinal compressive strength	605	MPa
Normal compressive strength	55	MPa
Longitudinal tensile strength	656	MPa
Normal tensile strength	55	MPa

Table 2: Class 12.9 fasteners material model.

Parameter	Value	
Density	7,85E-09	tonn/mm ³
Young modulus	2,10E+05	MPa
Poisson's ratio	0,33	-
Yielding strength	1080	MPa
Failure strength	1200	MPa
Plastic deformation at failure	0,08	-

Table 3: 100 HV hard washers material model.

Parameter	Value	
Density	7,85E-09	tonn/mm ³
Young modulus	2,10E+05	MPa
Poisson's ratio	0,33	-
Yielding strength	235	MPa
Failure strength	360	MPa
Plastic deformation at failure	0,20	-

Table 4: Numerical and experimental average loads.

Insert size	Maximum force [kN]		Error
	Experimental (average)	Numerical	
M5	10,40	10,04	3,44%
M6	25,01	24,62	1,56%
M8	43,45	40,55	13,24%



Fig. 1. Threaded metal inserts type: Keensert[®] (a), Kobsert[®] (b), Time-sert[®] (c).

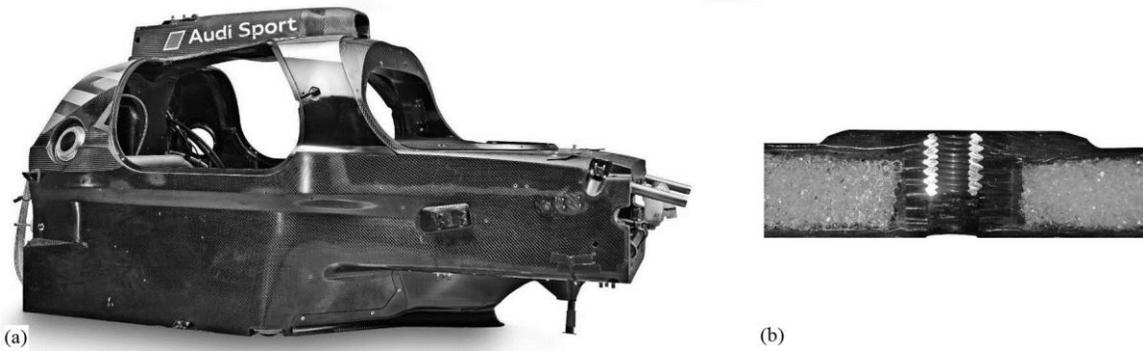


Fig. 2. Threaded inserts application in the frame of a racing car [4] (a). A detail of an installation of a threaded insert in a sandwich panel (b).

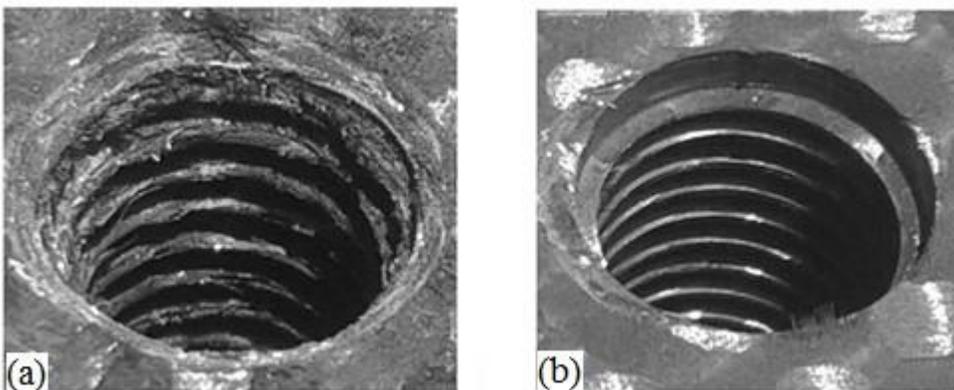


Fig. 3. Threaded holes (M8) realized in a 30 mm thick carbon fibre laminate by: tapping (a) and milling (b).

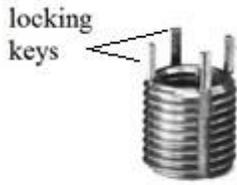


Fig 4. Keensert® lightweight locking keys. Pushed down through the material to lock the insert rotation.

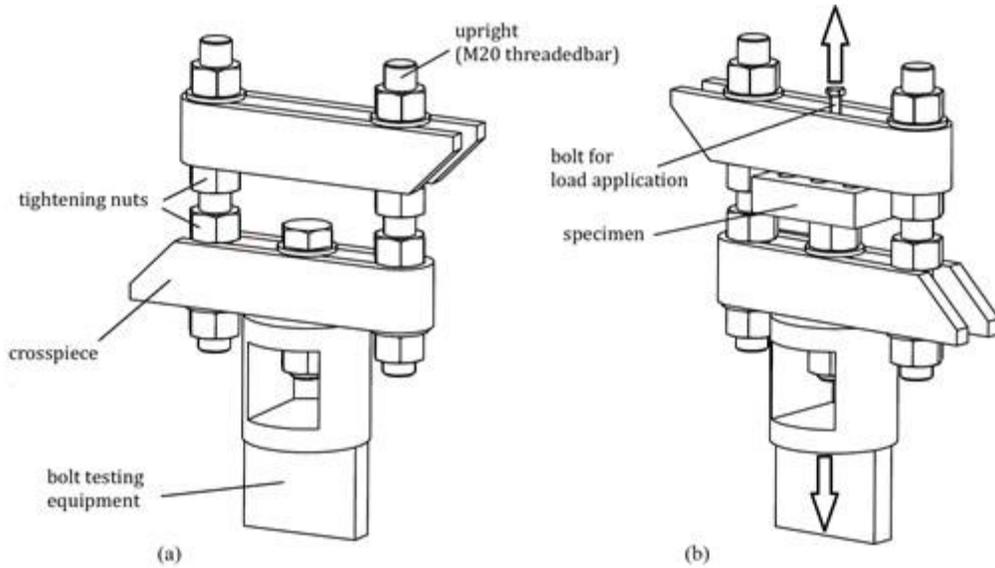


Fig 5 Pull-through test equipment.

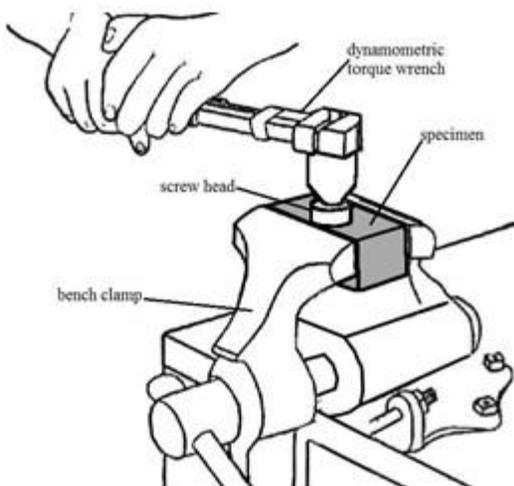


Fig 6 Torsion test equipment.

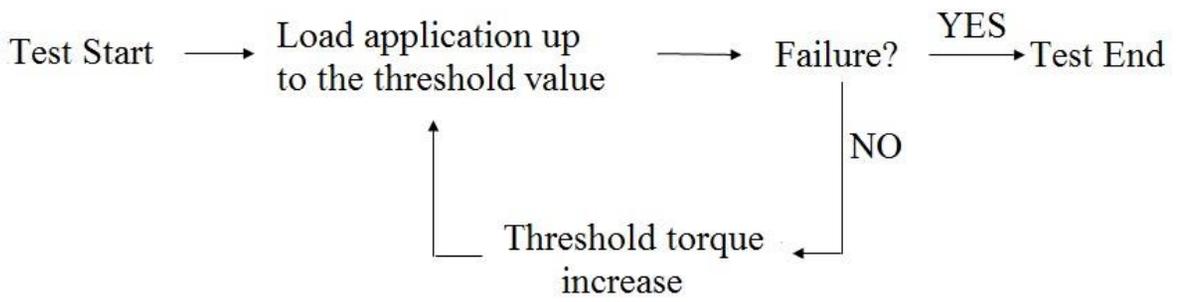


Fig 7 Torsion test iterations.

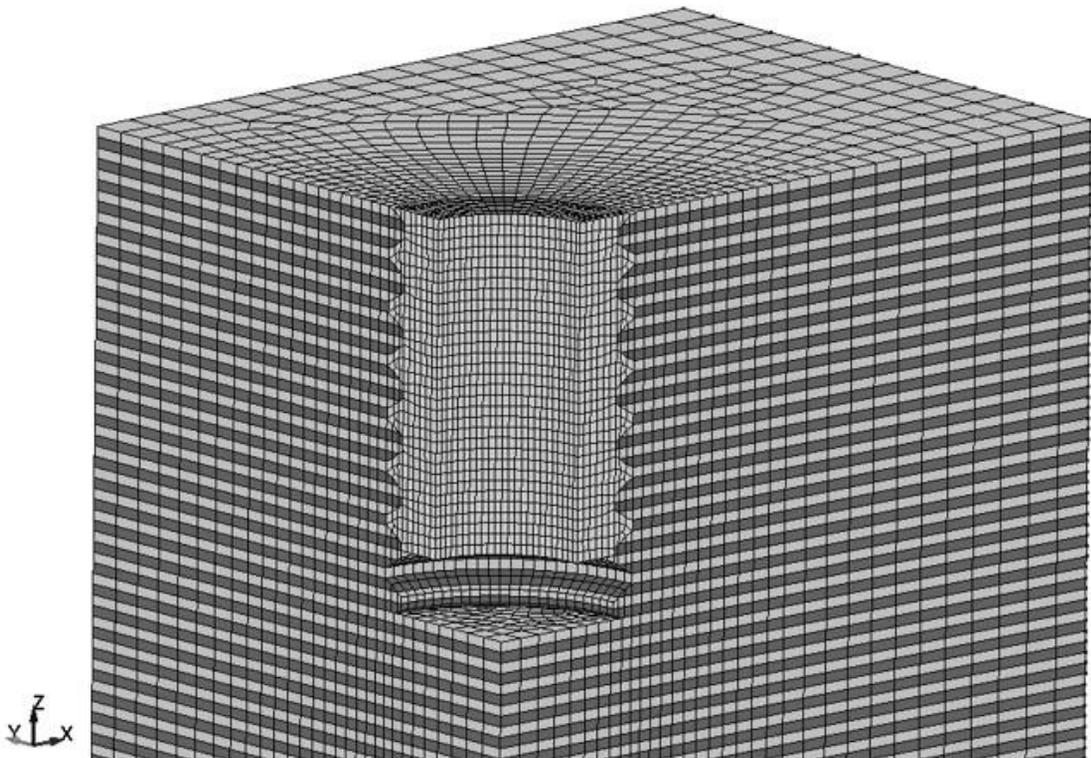


Fig. 8: Insert and laminate discretization.

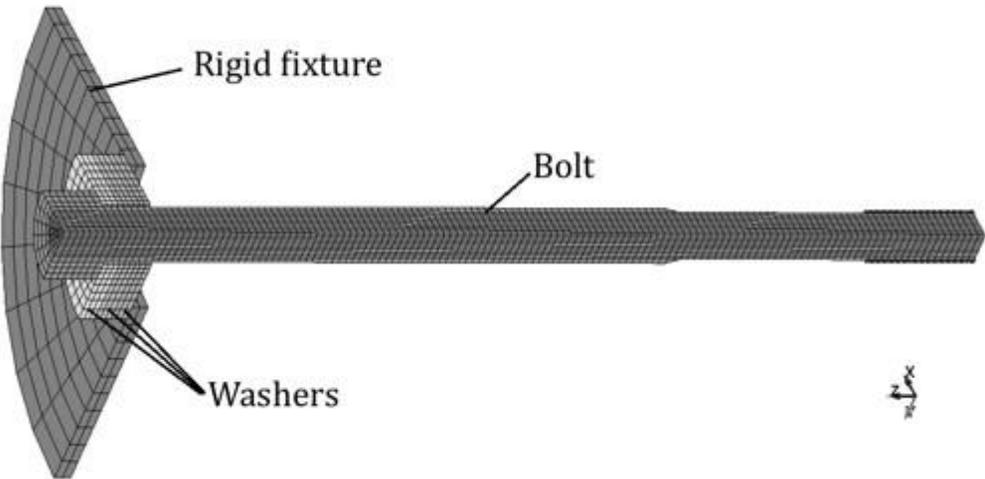


Fig. 9: Bolt and washers model.

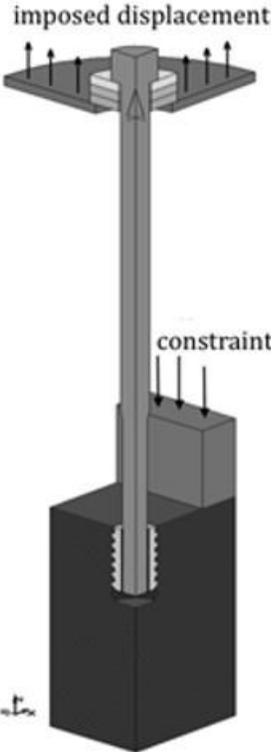


Fig. 10: Full model.

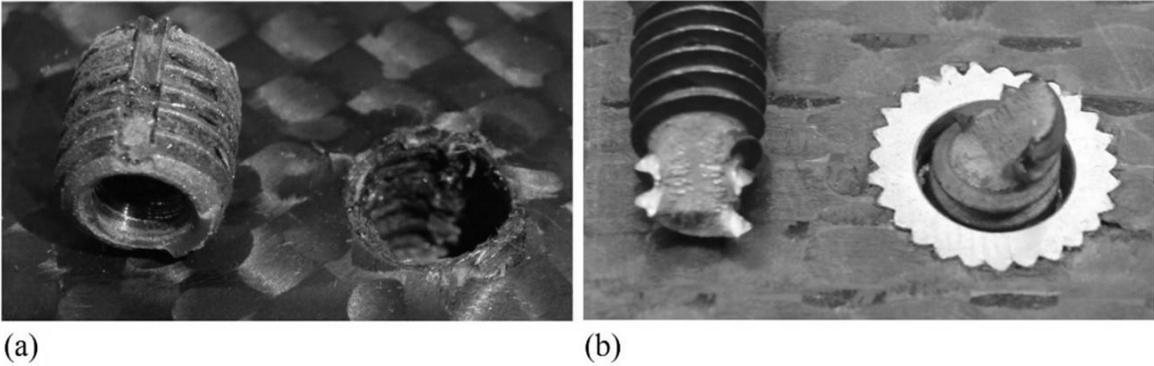


Fig 11. Junction failure: insert extraction (a) and bolt rupture (b).

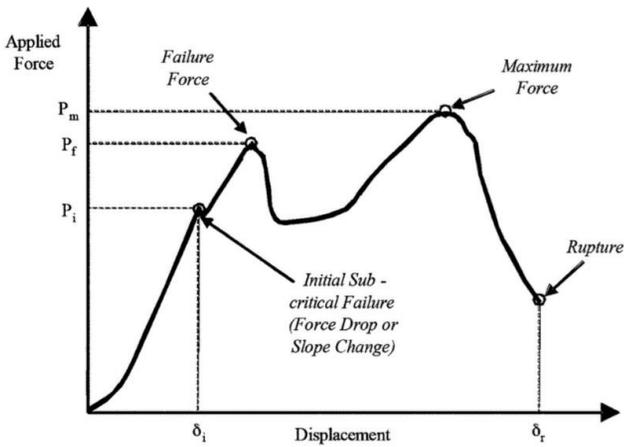


Fig. 12. Typical force vs. displacement behaviour [3].

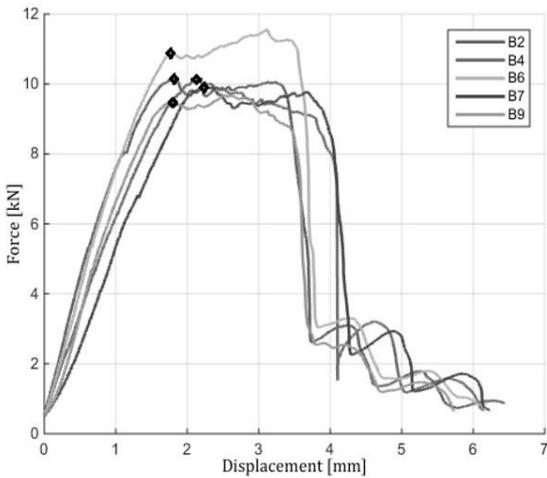


Fig. 13: Force vs. Displacement behaviour of Keensert® M5 at the state of the art. Every curve comes from a different test. Black dots indicate the failure force.

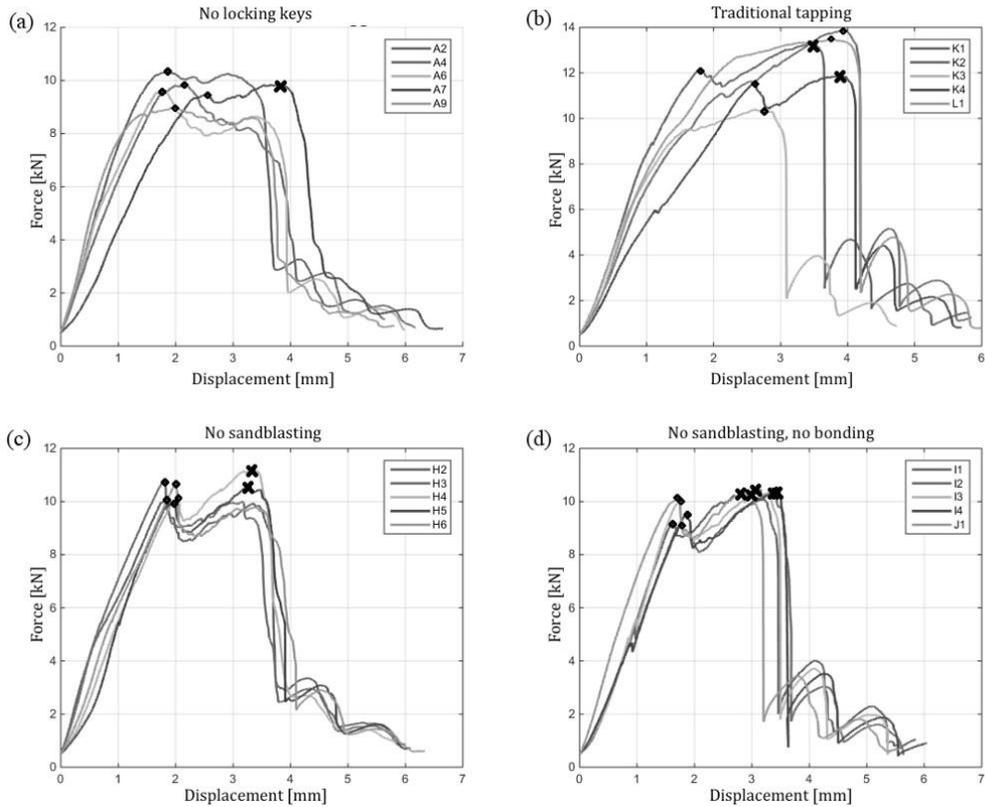


Fig 14. Force vs. Displacement behaviour of Keensert® M5 for different installation modes: no locking keys used (a), traditional tapping (b), no sandblasting (c), no sandblasting, no bonding (d). Black dots indicate the failure force. Black crosses, if present, indicate the maximum force.

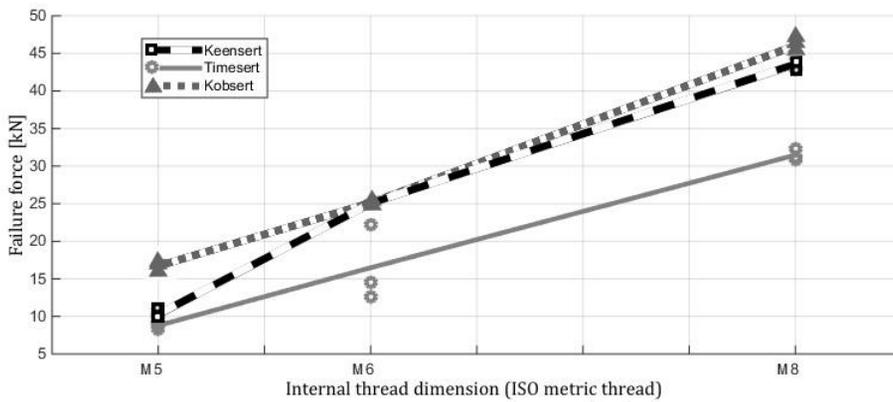


Fig 15. Failure force for Keensert®, Time-sert® and Kobsert® for different sizes. Circles indicate experimental values and the solid lines connect mean values.

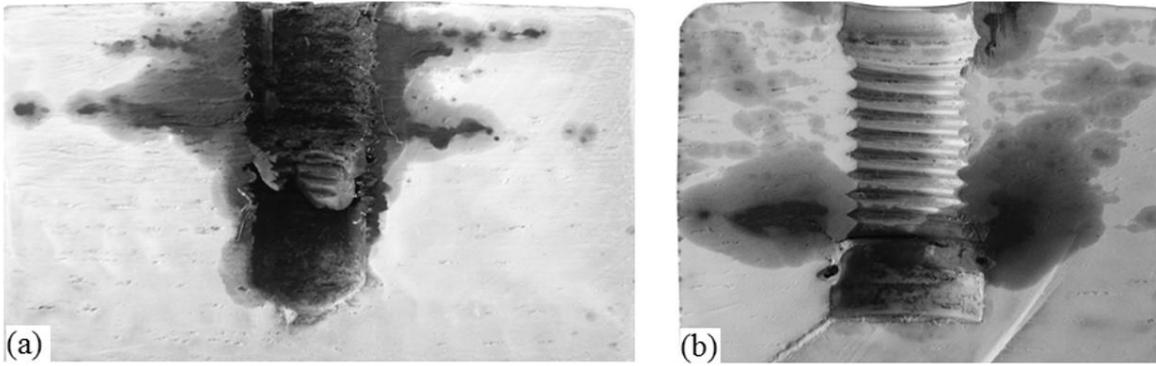


Fig. 16: Damaged area about the insert hole after insert (a) and bolt (b) pull-through.



Fig. 17. Bolt failure in torsion tests.

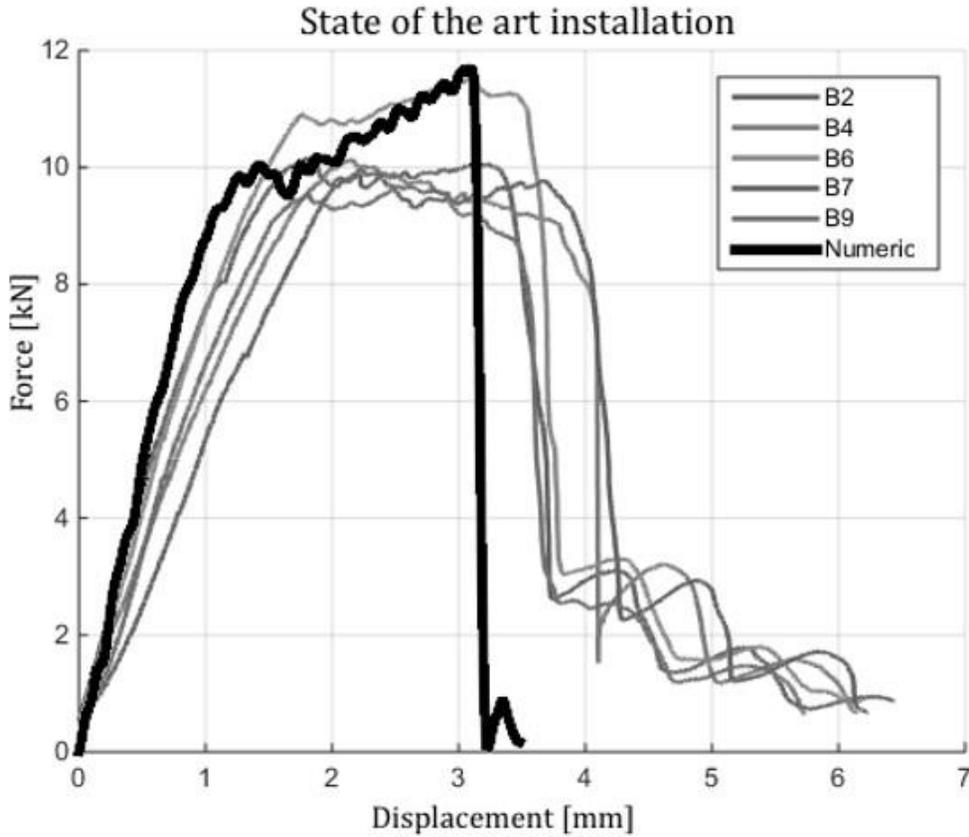


Fig. 18: Numerical-experimental comparison of M5 model.

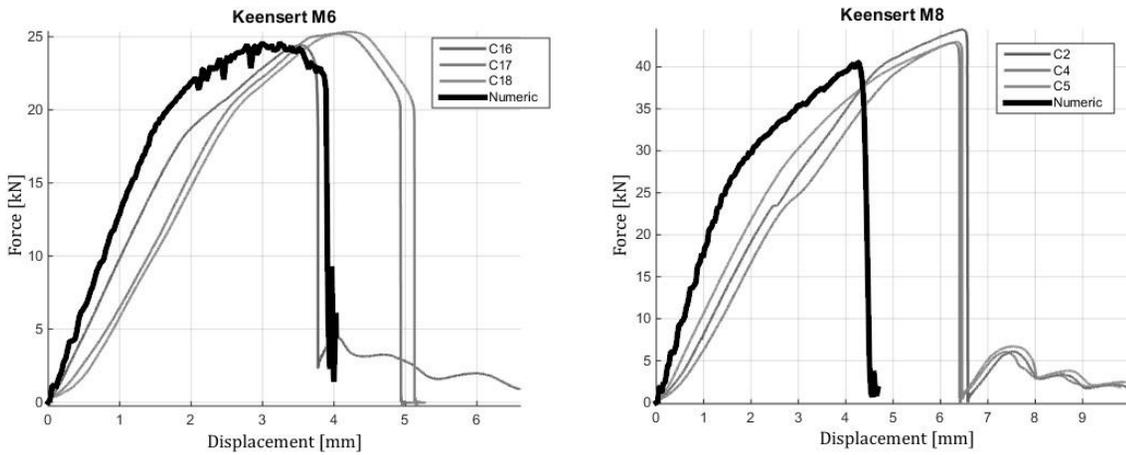


Fig. 19: Numerical-experimental comparison of M6 and M8 model.

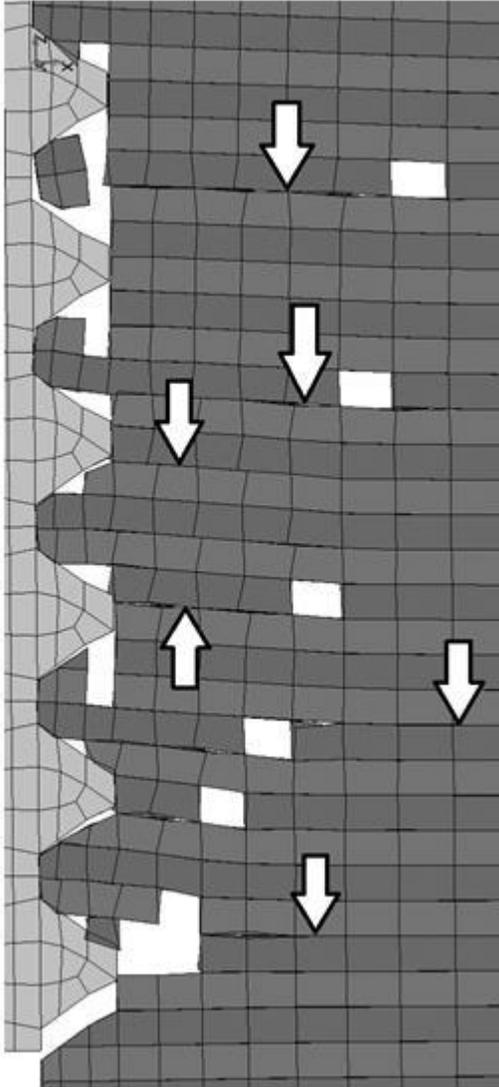


Fig. 20: Damaged zone around the insert. Arrows highlight zones where delamination has occurred.

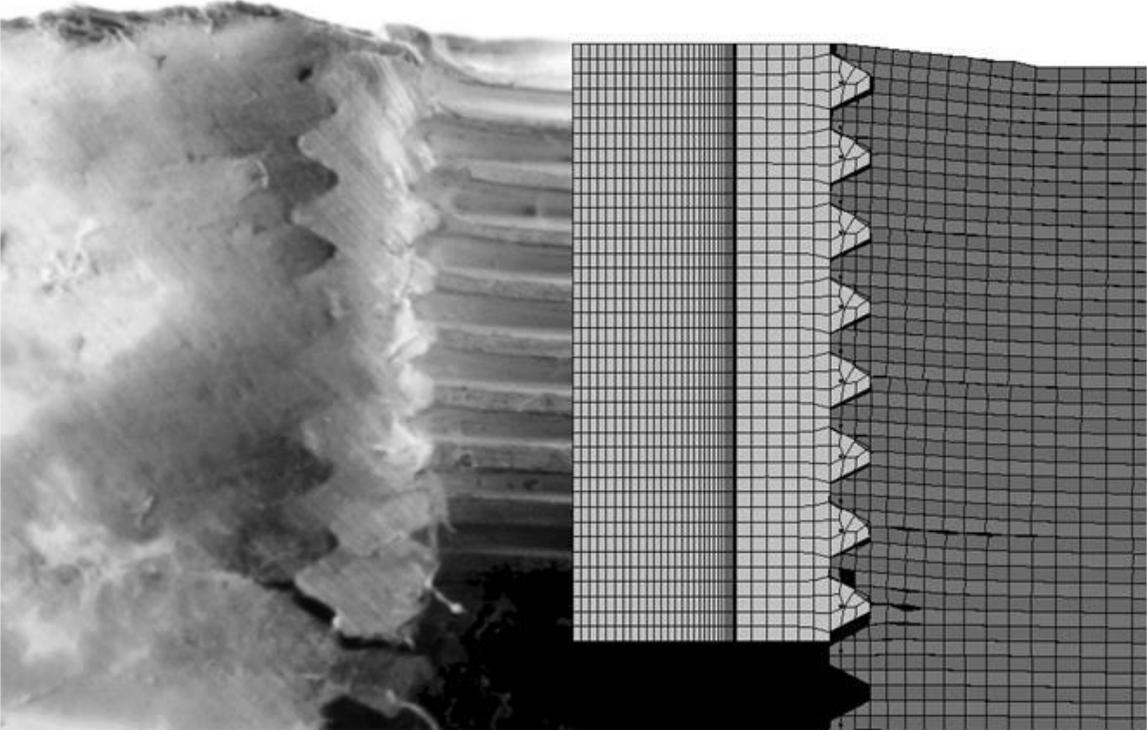


Fig. 21: Comparison between real damage and numerical one.