

Adhesive Connections in Timber: A Comparison between Rough and Smooth Wood Bonding Surfaces

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Abstract—The use of adhesive anchors for wooden constructions is an efficient technology to connect and design timber members in new timber structures and to rehabilitate the damaged structural members of historical buildings. Due to the lack of standard regulation in this specific area of structural design, designers' choices are still supported by test analysis that enables knowledge, and the prediction, of the structural behaviour of glued in rod joints. The paper outlines an experimental research activity aimed at identifying the tensile resistance capacity of several new adhesive joint prototypes made of epoxy resin, steel bar and timber, Oak and Douglas Fir species. The development of new adhesive connectors has been carried out by using epoxy to glue stainless steel bars into pre-drilled holes, characterised by smooth and rough internal surfaces, in timber samples. The realization of a threaded contact surface using a specific drill bit has led to an improved bond between wood and epoxy. The applied changes have also reduced the cost of the joints' production. The paper presents the results of this parametric analysis and a Finite Element analysis that enables identification and study of the internal stress distribution in the proposed adhesive anchors.

Keywords—Glued in rod joints, adhesive anchors, timber, epoxy, rough contact surface, threaded hole shape.

I. INTRODUCTION

TIMBER is an eco-friendly building material and nowadays timber structures represent one of the most typical examples of sustainable construction.

Carpentry joints, made by the workability of wood surfaces in contact, and traditional mechanical joints such as screws, bolts, nuts, aluminium angle brackets and perforated plates are the most common connection systems used in wooden structures [2].

In some applications these traditional joints can become complex, unaesthetic and do not correspond to the original design calculations. Taking into account that usually the majority of the design efforts can be spent on joints, as they are a critical part of the whole structure design, timber engineering needs improvements and renovations in connection systems.

Glued in rod joints can be the answer to this issue [3].

Glued in bolts are new mechanical timber joints, composed of steel rods or fibre reinforced polymers and glue (Fig. 1).

Steel bars are embedded into adhesive-filled holes in wood elements [3]. Commonly the predrilled holes are wider than the diameters of the bars [4] and the distance between the steel and timber corresponds to the glue line thickness.

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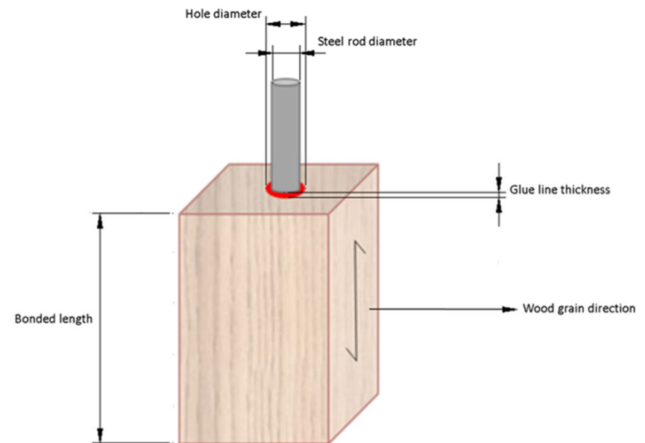


Fig. 1 Glued in rod joint

If properly designed, this connection system is characterised by ductile behaviour and high stiffness values without showing the presence of an initial settlement phase. Other benefits are represented by a total invisibility of the joint which improves its aesthetic quality [5], and by a competitive production cost [6].

Compared to traditional connectors, for glued in bolts the stress is distributed along all the bonded length preventing stress concentration points near anchor bolts of mechanical joints. This joint also provides good protection from fire and from corrosion of embedded steel elements [5]. Nevertheless, strict quality control of the correct manufacture of the joints, during test analysis and in situ, remains one of the critical issues for this adhesive connection [7]. The application of resin connectors is increasing in the new glulam construction field to design a different solution of rigid joints for timber to timber connections such as 'in glulam plane grid structures' or 'in moment-resistant corner joints of portal frames' [8] where there is an intersection between structural members.

II. STATEMENT OF THE PROBLEM

The main issue for the glued in bolt connection system is the lack of standard regulation in this specific structural design sector [7]. Despite progress in the field, the European Standard, EN 1995 (EC5) for the structural design of timber, currently does not provide established technical rules for glued connections.

Resin connectors have been in use since the 1970s without a precise design method [16]. Designers' choices have been supported by destructive test analysis that enables the knowledge and prediction of the resistance capacity of the

joint. Many studies and several experimental activities have been carried out in recent years leading to various design equations and sometimes contradictory conclusions [1]. This inaccuracy indicates that more information and further experimental tests are required to gain a proper knowledge of this topic.

III. EXPERIMENTAL ACTIVITY

A new experimental test has been conducted on ten wooden sample pieces of 1000 cm³ volume (Fig. 2) to study the performance of a new prototype of adhesive anchors in timber and to compare its load capacity to 'traditional' glued-in-rod joints, identified with smooth and cylindrical bonding surfaces.

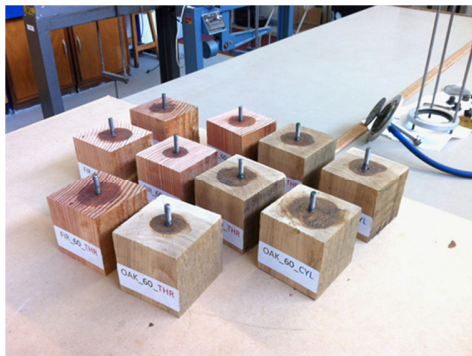


Fig. 2 Samples of glued in rod joints for testing

The adhesive joint prototypes are characterised by the use of an 8 mm steel bar, epoxy adhesive and a threaded shape for its internal borehole.

The modifications of too many parameters in the joints geometry and features (such as bar distances from edges, several steel bar diameters and adhesive types) could lead to having too many variables, producing different results from the testing experiments that are not comparable. For this reason, the study has been focused on a critical analysis of the followed parameters:

- Hole shape and bonding surface properties (smooth, rough)
- Different timber species (Oak, Douglas Fir)

The new hole shape in the timber element has been realised by a drill using a specific drill bit (Fig. 3). The result obtained from the use of this specific drill bit is a rough internal surface in the wooden sample (Fig. 4). This new contact surface between timber and epoxy should provide an improved adhesion between the two materials because, usually, through surface roughening techniques it is possible to achieve the best bond conditions in wood [15].

Past research studies [9] on glued in rod connections had often used a smooth cylindrical borehole without considering that the properties of the contact surface could affect the bond and, consequently, the joint's pull-out capacity.

The new threaded shape should provide a slightly increased contact area and a decrease in the shear stress at the contact surface between timber and adhesive. At the same time, the

new threaded hole has a smaller volume than the cylindrical one and it would require a reduced use of resin and, therefore, a significant abatement in the joints cost production.



Fig. 3 Specific drill bit for woodworking used to create the new threaded hole shape

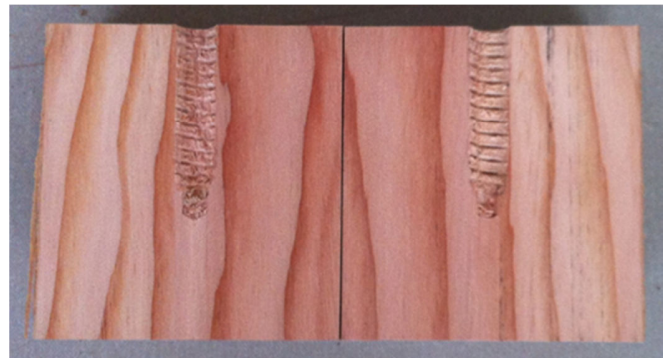


Fig. 4 Rough and threaded surface created in the timber samples by using the specific drill bit

The experiment is aimed at analysing the different joints' behaviour and assessing which one performs best in term of strength and stress response.

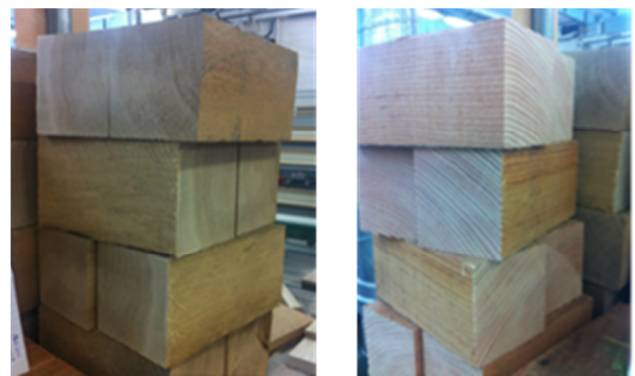


Fig. 5 Oak (left) and Douglas Fir samples (right)

The two different timber species that have been chosen to conduct the tests are Oak, the most common hardwood species that historical churches and buildings are made of, and Douglas Fir, one of the most used softwoods for construction (Fig. 5). The moisture content of each species has been recorded and taken into careful consideration as it has been

found [10] that it is one of the most important parameters that can affect the structural behaviour of timber in real application. The moisture contents of Oak and Douglas Fir samples were assessed, by using a pin-type moisture meter, before starting the experimental activity and showed very similar results.

The average moisture content is around 7% for both species (Oak average moisture content: 7.5%; Douglas Fir average moisture content: 6.9%) and it is an appropriate moisture content value to classify the wooden samples in Service Class 1 and 2, which are the Service Classes recommended in the Eurocode 5 for adhesive connection applications [3], [10].

In addition, this similar moisture content value is a significant requirement to consider the two different species comparable.

IV. MATERIALS AND TESTING METHOD

A. Materials

The samples (Fig. 6) have been assembled using

- Oak (density: 690kg/m³)
- Douglas Fir (density: 570 kg/m³)
- 8 mm stainless steel bar (A2 Grade Type 304S15, max tensile strength: 520-750 N/mm²)
- epoxy resin (density: 1.5 g/cm³, compressive strength 7 days: 95 N/mm², tensile strength 7 days: 23 N/mm², flexural strength 24 hours: 45 N/mm² [11])
- drill
- 8mm cylindrical drill bit
- 12mm threaded drill bit
- 5 Oak specimens: 2 cylindrical hole shape and 3 threaded hole shape
- 5 Douglas Fir specimens: 2 cylindrical hole shape and 3 threaded hole shape

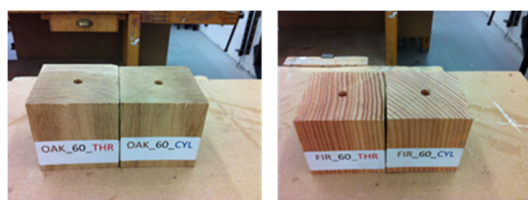


Fig. 6 Oak (left) and Douglas Fir samples (100 cm² cross section and 10 cm height) (right) drilled by using the specific drill bit (THR) and a cylindrical drill bit (CYL)

B. Installation Method for Glued in Rod Joints

The installation mode for glued in rod joints is another critical aspect that has to be considered during any practical application of adhesive anchors.

The sample's preparation has followed a particular installation method (Fig. 7). The new hole shape and the insertion of some plastic ring supports in the joint have allowed the steel bar to maintain a perfect vertical position without having to fix it in place during the resin curing time. A specific installation method for glued in rod joints has not been suggested by any other research studies up to now, but finding a solution for practical issues and providing standard

installation rules can represent a great achievement to improve the practical installation of resin connectors in situ.

Installation Method:

1. Drill a pilot hole choosing the steel bar diameter and a depth length that is 1 cm deeper than the designed embedded length. This step will provide a base for the steel bar insertion.
2. Drill a second hole to the designed shape, diameter and depth.
3. Clean the hole through several blows and brushes.
4. In the hole cleared from any timber dust, insert the epoxy following the installation method suggested by the manufacturing company [11].
5. Insert the threaded steel bar twisting with a back and forth movement until the end of the hole. [11]
6. Insert a specific plastic cylinder through the steel bar to the joint's surface. This support will help the bar to maintain a vertical position during the resin curing phase.



Fig. 7 Suggested installation method for glue in rod joints

It is important to underline that all timber samples have been drilled in parallel to the wood grain. The glued length is 60mm for all samples and the epoxyresin, manufactured by 2K Polymer Systems Limited [11], has been used in the studied adhesive connections with a thickness of 2 mm for the cylindrical hole samples and a variable thickness between 0.6 mm and 2 mm for the threaded hole specimens.

C. Testing Method



Fig. 8 Pull-out testing machine

The samples have been tested by a pull-out testing machine (Fig. 8) with a specific loading rate of 0.2 kN/sec to assess the

pull-out capacity of each joint's prototype. All tests have been performed as confined tests, therefore in a pull-compression test regime.

TABLE I
TEST RESULTS

Sample	Glued Length [mm]	Glue line Thickness [mm]	Contact Area [mm ²]	Moisture Content [%]	Failure Load [kN]	Mean Failure Load [kN]	Displacement [mm]	Mean Displacement [mm]	τ Adhesive/Wood [N/mm ²]
FIR CYL1	60	2	1885	6.9	28.41	27.58	9.36	9.37	15.07
FIR CYL2	60	2	1885	6.9	26.75		9.39		14.19
FIR THR1	60	var 0.5-2	2026	6.9	27.95		9.72		13.80
FIR THR2	60	var 0.5-2	2026	6.9	28.83	28.43	8.93	9.32	14.23
FIR THR3	60	var 0.5-2	2026	6.9	28.51		13.12		14.07
OAKCYL1	60	2	1885	7.5	22.88		24.00		7.33
OAK CYL2	60	2	1885	7.5	25.12	9.12		13.33	
OAK THR1	60	var 0.5-2	2026	7.5	23.81	8.53		11.75	
OAK THR2	60	var 0.5-2	2026	7.5	25.79	24.93	8.66	8.55	12.73
OAK THR3	60	var 0.5-2	2026	7.5	25.18		8.46		12.43

V. TEST RESULTS

The test results in Table I show that joints made from Douglas Fir performed better, having failure load values slightly higher than the Oak joint samples.

A decrease in the values of shear stress between adhesive and timber would maximise the joint's pull-out behaviour and a lower shear stress might be achieved with an increase in the joint's embedded length.

Due to the confined test conditions, the values shown in the results table tend to overestimate the true strength of the joints. For this reason, it is important to highlight that all results obtained from tests performed in confined regimes should be adjusted by reduction factors in order to obtain reliable results.

Furthermore, this experimental activity proves that the change in the hole shape has led to having roughly the same contact area of the cylindrical hole but a critical reduction in the hole volume.

VI. DISCUSSION

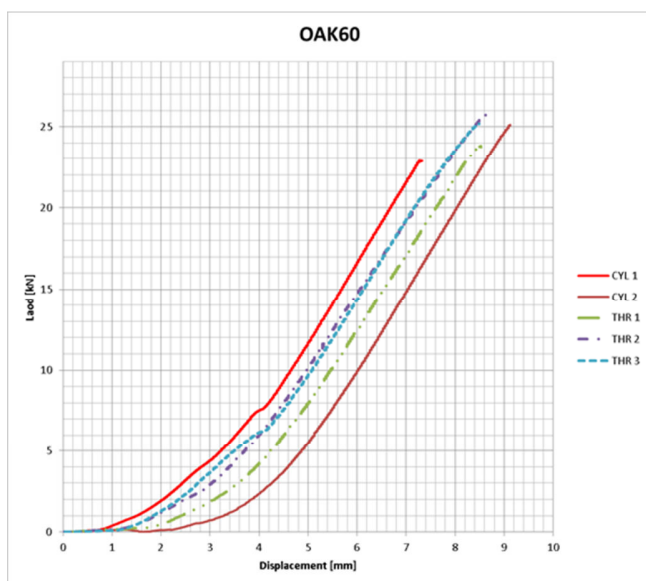


Fig. 9 Load-Displacement relationship in Oak samples

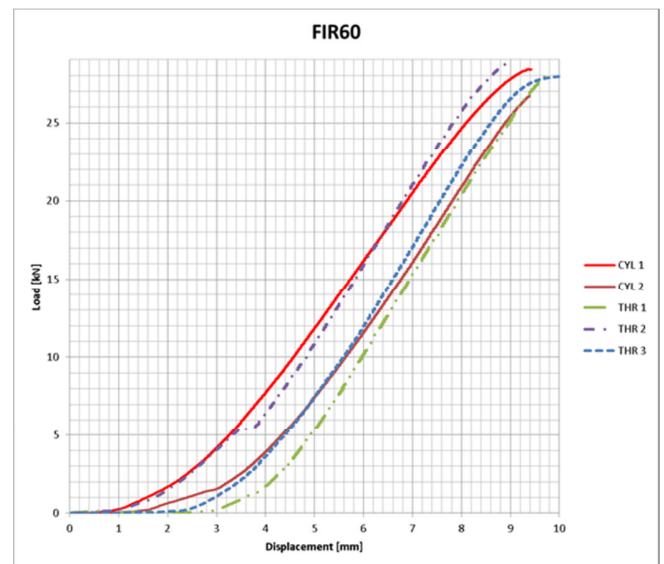


Fig. 10 Load-Displacement relationship in Douglas Fir samples

The graphs obtained from the results analysis (Figs. 9, 10), do not show a visible improvement in the pull-out capacity of the joint for the new threaded shape. It is possible to observe that the mean failure loads for both prototypes, cylindrical and threaded, are very similar.

On the other hand, the threaded joint has a great advantage: it has led to a 30% reduction in the use of resin. In effect, in this specific test, the effective hole volume, calculated by deducting the steel bar volume from the entire borehole volume, was reduced by 30%, from approximately 3143 mm³ (cylindrical shape) to 2224 mm³ (threaded shape).

The load-displacement graphs (Figs. 9, 10), obtained by the pull-compression confined tests on the joint samples, show the similar behaviour of the anchor connections in terms of stiffness.

It is possible to observe that the load-deformation curve slopes are all parallel to each other following the same trend in each test.

The variation of the borehole from a cylindrical to a threaded shape for a 60 mm embedded length has not affected the stiffness of the joints. However, the threaded borehole samples showed a regular trend in the pull-out test results, whereas the cylindrical samples had a variation in their results.

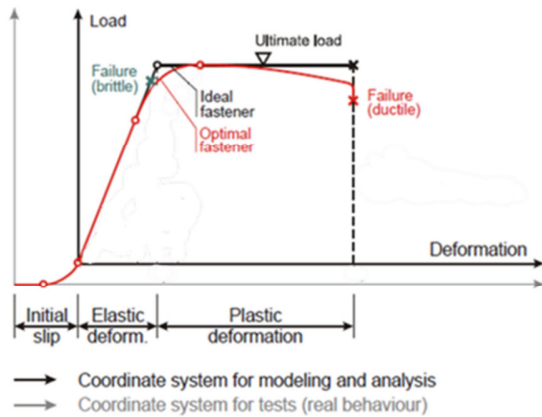


Fig. 11 Typical 'load-slip-curve of fasteners' [13]

Fig. 11 presents the typical 'load-slip-curve of fasteners' that can help to understand the mechanical behaviour of joints.

Comparing the curves in the graphs to the typical 'load-slip-curve of fasteners', it is possible to notice that all the samples had a brittle failure mode.

Stainless steel bars with high tensile strength had been chosen for this experimental activity to study the bond between resin and timber and, for this reason, the failure had occurred in timber members. In real applications, using bars with lower steel grades would lead to having the failure in the steel bar and, therefore, a ductile failure mode of the glued in bolt joint [12].

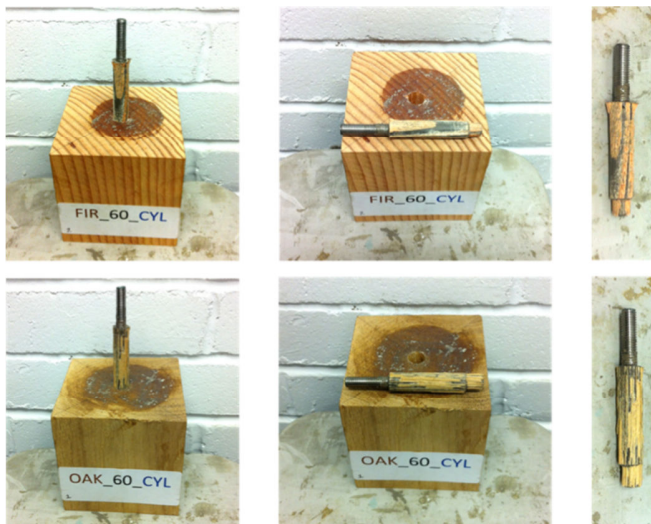


Fig. 12 Failure mode in Oak (bottom) and Douglas Fir (above) samples with smooth and cylindrical borehole after being tested by a pull-out test

Fig. 12 shows the cylindrical joint samples after being tested by a confined pull-out test.

The Oak and Douglas Fir specimens present similar results. It is interesting to note and study all features of the contact surface between timber and resin. For example, the quantity of timber that remained stuck with the hardened resin can provide information regarding the bonding quality.

In this specific case, the low quantity of wood around the resin and its inconstant distribution proves a poor bond strength between resin and Douglas Fir and between resin and Oak timber. The contact surface between resin and timber in the cylindrical joint samples is characterised by no identifiable properties that belong both to resin and timber.

The cylindrical and smooth surfaces, drilled parallel to the timber grain in each wooden sample, do not provide a strong bond and do not represent the optimum bonding surface for an adhesive connection.

On the other hand, the threaded hole shape provides to the threaded joint prototypes (Fig. 13) a rough internal contact surface that allow the resin to adhere consistently through the wood fibres.



Fig. 13 Failure mode in Oak (bottom) and Douglas Fir (above) samples with rough and threaded borehole after being tested by a pull-out test



Fig. 14 Wooden parts attached to the hardened resin on the steel bar in the threaded samples in Oak (left) and Douglas Fir (right)

The wooden parts attached to the hardened resin on the steel bar in the threaded samples are significantly visible and

sizeable (Fig. 14). The bond layer is mainly represented by timber material. This critical detail could be useful during the design calculation of the pull out capacity of the joint. In this case, it would be correct to categorise the failure mode of the joint as a failure of the timber material close to resin surface.

The material at the contact surface can be considered as a hybrid material made of timber and epoxy, therefore it has to be classified with a shear strength parameter that is influenced by both timber and epoxy mechanical properties.

The understanding of the contact surface properties between wood and glue still represents the main problem for the prediction of the pull-out capacity of adhesive anchors. Many proposed design rules [14] tend to be overly conservative because they only take into consideration the shear strength value of wood.

VII. FINITE ELEMENT ANALYSIS

A Finite Element (FE) analysis has been used to study the behaviour of the joint prototypes.

The material properties of the Finite Element model used in this analysis have been characterised by a bilinear kinematic model for wood, a bilinear isotropic model for steel and a linear isotropic model for resin.

The new threaded hole joint has been modelled using Ansys, a widely known FE program, and its output results have been compared to the cylindrical hole connection outcomes.

Fig. 15 shows the cylindrical and the threaded joint models. After setting appropriate boundary conditions, the same displacement was applied, in both models, at the top of the steel bar in order to recreate a pull-out test on both samples. The results showed the change of shape has not significantly increased the pull-out capacity of the joint. Nevertheless, it is possible to notice that the stress distribution along the length has changed and, in the threaded shape, the stress is less concentrated at the top section of the joint but spread further along the joint's embedded length.

VIII. CONCLUSION

- Douglas Fir joint samples reached the highest pull-out values during this specific experimental test.
- An improved bond condition between timber and resin has been reached using an irregular and rough surface for the pre-drilled borehole in the timber samples.
- For timber samples characterised by short lengths, threaded hole joints have performed slightly better than the cylindrical hole joints.
- The new threaded hole joints have approximately the same pull-out capacity of cylindrical hole joints but they require 30% less resin. This saving is a significant abatement in the joint's cost production.
- The FE models indicated that the new threaded shape can prevent stress concentrations at the top section of the joint.

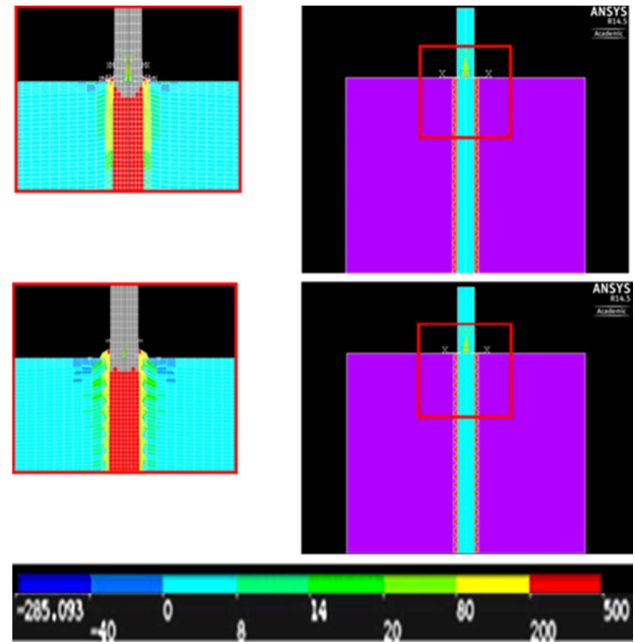


Fig. 15 Finite element models of glued in rod joint with threaded borehole (bottom) and cylindrical borehole (above). The scale range is expressed in MPa

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