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Abstract

Fiber-reinforced foamed urethane (FFU) sleepers are one of the new bespoke composite sleepers designed as a replacement alternative to timber sleepers with better mechanical properties and durability. This paper is the first to conduct both experimental and numerical studies into the structural integrity of fastening systems used in conjunction with FFU composite sleepers. In this study, 24 FFU specimens have been used for screw pull-out tests. Digital image correlation (DIC) is adopted to investigate the influences of critical parameters such as wet sleeper, sleeper drilled hole diameter (18 and 20 mm) and screw active length (80, 90 and 110 mm) inside sleeper. The pull-out test results reveal that 0.3% moisture content in FFU specimens can decrease the pull-out strength around 18%, 19%, 6% and 13% between dry and water-absorbed specimens of 18-AD and 18-AW, 18-BD and 18-BW, 20-CD and 20-CW, and 20-BD and 20-BW, respectively. Specimens with 20 cm hole have the highest pull-out loads of 71.9 kN and 68 kN in dry and water-

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absorbed states, respectively. Although the active length of the screw decreases from 110 mm to 90 mm, the pulling strength may decrease only around 14% and 16% for dry and water-absorbed states, respectively. Sensitivity analyses exhibit that a reduction in elastic modulus and density of FFU specimens can decrease pull-out resistance of FFU specimens.

Keywords: Railway tracks, Fastening system, FFU sleeper, Pull out test, FEM

Introduction

Railway timber sleepers have been used for nearly two centuries worldwide and there are millions of old timber sleepers at the end of their service life in railway lines that need to be replaced (Manalo 2011). However, good quality timber as a convenient replacement for the current timber sleepers has become scarce and more expensive. Railway authorities thus seek alternative materials that can be implemented in special locations under aggressive and hostile dynamic load conditions. To date, several composite railway sleepers have been developed as alternative railway sleepers in special locations such as switches and crossings, bridge ends, stiffness transition zone, and on the viaduct with restricted vertical space (Jing et al. 2020). Some examples of composite sleepers are recycled plastic sleepers, FFU sleepers, Carbonloc composite sleepers, and so on (Ferdous et al. 2015).

FFU composite sleepers have been adopted as an option for timber sleepers replacement in railway switches and crossing (Kaewunruen and Liao 2021). The field installation of the FFU composite can be observed in various countries such as in Australia, Germany, Japan, and the UK. Recently, FFU sleepers have been adopted in different parts of railway tracks such as bridge deck (Otter 2012) (SEKISUI 2021), switch and crossing (Kaewunruen 2014; Kaewunruen et al. 2017), subways (Koller) and conventional railway tracks (Jing et al. 2021). FFU composite was developed in 1978 to be used in railway track, and for the first time, it has been used in 1.3 km railway tracks in Japan since 1985 (Koller 2009). This kind of sleeper is also getting popular in other countries such as China, Taiwan, the USA and the rest of Europe. In China, FFU sleepers have been installed on a long-span railway bridge in Chongqing city (Liu et al. 2012). These sleepers have been installed in European railway tracks since 2004 started from Vienna, while Germany installed FFU sleepers on bridges and turnouts since 2011 (Koller 2015). FFU sleepers are manufactured from longitudinal long continuous glass fiber reinforcement and random fiber in the transverse direction within hard type poly-urethane foam (Takai et al. 2006). This type of sleeper has several advantages compared with traditional railway sleepers (wooden, steel and concrete sleepers) such as easy to drill and cut, good durability, higher flexural strength and modulus of elasticity, lightweight, good resistance to water absorption, heat and corrosion, and its longer than 50 years of service life (Ferdous et al. 2015). The Sekisui FFU sleepers, specifically, use screw with 20 mm diameter and 80 mm active length similar to 20-BD specimen of this study (Koller 2009) while Queensland Rail's screws are most similar to 18-BD specimen of this study with 18 mm diameter screw and 80 mm active length (Murray 2006), and China uses both 18-BD and 20-

BD systems (Liu et al. 2021).

(Kaewunruen and Liao 2020) compared the sustainability of concrete bearers and FFU sleepers in railway switches and crossings based on the calculations of CO_2 emissions and energy consumption. Results showed that using FFU material leads to higher initial energy consumption and CO_2 emissions than concrete. But, the high maintenance frequency and relatively low lifespan of concrete sleepers resulting in higher energy consumption and CO_2 emissions during their lifespan. (Yu et al. 2021) assessed screw pullout behavior of FFU sleepers because the limited understanding of this topic is one of the main barriers in front of the wide adoption of available composite railway sleepers. Because low shear strength parallel to the longitudinal fibers, a linear to non-linear change pull-out behavior was detected identified by load decrease and loss of stiffness before 20kN. This change specified the initiation of minor cracking. (Kaewunruen 2014) investigated the acoustic and dynamic characteristics of FFU sleepers, finally, it is concluded that FFU composite sleeper performance is almost equivalent to that of a hard-wood timber sleeper. In another study by (Kaewunruen et al. 2020), the dynamic properties of FFU specimens were investigated in wet and dry states. Therefore, FFU specimens were immersed in deionized water for 24 hours resulting in 1-3% water absorption. Final results show that the water absorption affects damping behaviour and natural frequencies of the FFU specimens up to 4% and 7%, respectively, under wet/dry conditions. (Koller 2009) reviewed some recent studies on FFU sleepers. The fatigue, electrical and impact resistance of FFU sleepers obtained from laboratory experiments were presented. The impact test results showed the stability of FFU sleepers which demonstrates the constancy of the track gauge as there were no signs of warping or twisting as a result of the impact loads. In the case of fatigue resistance, the FFU sleepers did not have any cracks after two million cyclic loads. In addition, the electrical resistance of FFU synthetic wood was calculated as a value of 71.9 k, which satisfies the minimum permissible value. (Jing et al. 2021) investigated lateral resistance of FFU sleepers with different optimized shape. The FFU sleeper with trip block at the bottom surface increased lateral resistance of sleeper. Transportation technology center, Inc., (TTCI 2021) investigated long-term behavior of FFU sleepers on bridge deck since 2009. It showed that FFU sleeper had a good resistance against track loads. The FFU sleepers had an average middle deflection by 0.35 cm accumulated after more than 1200 million gross tons (MGT).

Several limitations on application of FFU sleeper have been addressed so far such as their higher price (Gerard and Mckay 2013), lower shear strength and shear modulus due to the lack of transverse directional fibers and their compliance with occupational health, safety and environment (OHSE) guidelines (Sengsri et al. 2020).

Ballasted railway tracks may have several defects during their service life, such as fouled ballast, ballast breakage, hanging sleepers etc. (Esmaeili et al. 2020). One of the main problems in ballasted railway tracks that mostly causes the deterioration of timber sleepers is the poor drainage system (Sañudo et al. 2019). This problem is often caused by ballast contamination resulted from mostly ballast breakage and the combination of fine materials of the lower granular layer with ballast particles. Therefore, the voids between the ballast particles are filled (Paiva et al. 2015) which can lead to water trapped around sleepers, especially, in high-intensity raining spots as shown in Fig. 1. (Kaewunruen et al. 2017) reviewed the georisks under climate uncertainties, including increased rainfall, for railway sleepers. It is concluded that ballast-sleeper interaction can be negatively affected by incompressible fluid stagnant on tracks. Timber sleepers can be softened by adjacent water resulting in the soffit of the sleepers and the ballast-sleeper interlocking.

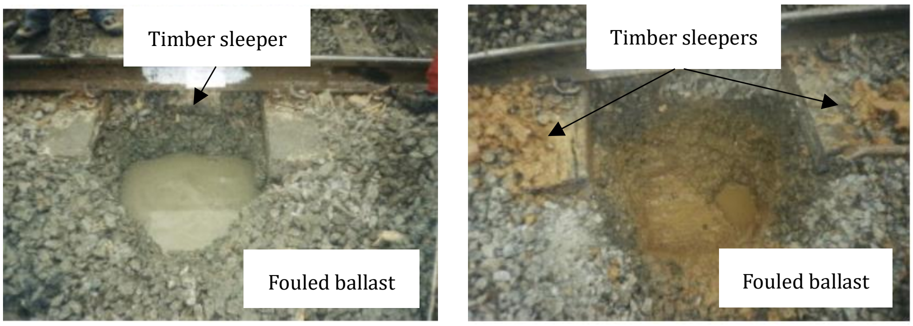


Fig. 1. The rainwater accumulated in the ballast layer (Paiva et al. 2015).

In addition, it can cause a corrosive environment for steel sleepers; reduce mechanical properties of timber sleepers; and may affect FFU sleeper performance as well, which will be emphasized in this current research.

Pull-out test is one of the main tests to recognize the fastening system's mechanical behavior within sleepers. The (AREMA 2013), (AS1085.22 2020), (CJ/T399 2012) and (JIS1203 2007) present the minimum pullout strengths for sleepers as 20 kN, 40 kN, 40 kN and 30 kN, respectively. (Ferreño et al. 2019) studied the behavior of the spring clip of the SKL-1 fastening system of concrete sleepers. The results presented that the fatigue of a spring clip under normal conditions is a very unlikely event. (Chen et al.) performed a series of pull-out test to obtain the relationship between the bolt ultimate pull-out capacity and the effective anchorage length. The results showed that the bending failure pattern different from the shearing failure pattern may occur when the dowel bears an extent of pull-out load. Furthermore, the ultimate pull-out ability of the dowel has a linear relationship with the value of rings for damaged thread, and the effective fastening length of the bolt. (Dersch et al. 2019) studied the background on the broken spike problems for timber sleepers. A validated FE model was developed to quantify the magnitude and location of spike stress concentrations. The results showed that the depth to the maximum stress concentration increases as the ratio of longitudinal to lateral load increases. (Lotfy et al. 2017) studied the interactions of plastic composite sleepers with the fastening system components to understand the behavior of these materials. The rail spike pull-out and lateral restraint for both screw and cut spikes were investigated. Screw spikes designed for composite plastic sleepers demonstrated very good performance, surpassing the minimum recommendations by AREMA. Technology University of München (Munchen 2008) investigated the pull-out resistance of the fastening system of the FFU sleepers. The average of 61 kN tensile load is reported for FFU sleepers pull-out strength.

According to the above-mentioned papers, FFU sleepers are strong enough that failure of which is a very unlikely event under normal conditions.

No research has ever addressed the fracture behavior of Fiber-reinforced foamed urethane (FFU) composite sleepers in pull-out test combined by digital image correlation (DIC) test in both dry and wet states. Therefore, this study is the first to specify the wet/dry influence on pull-out resistance of the material. Moreover, railway track fastening systems are mainly exposed to dynamic loads and both wet/dry conditions in reality. Thus it is critical to get the insight into their mechanical behavior with different screws and sleeper hole to assure the safety and workability. Wet FFU specimens have been assessed using pull-out tests and their fracture behavior is measured using the digital image correlation (DIC) test to measure crack strains and crack mouth opening displacement (CMOD). Two different diameters FFU sleeper holes as 18 mm and 20 mm and two different screw diameters as 22 mm and 24 mm are fixed in different active lengths of 80 mm, 90 mm and 110 mm, and are tested for wet and dry states. Therefore, FFU specimens are tested with almost 0.3% absorbed water by weight under the pull-out test to study whether it can influence its mechanical behavior. This sleeper material is known for its low water absorption, so they were kept for 3 days in the water basin. Concerning the low drainage of some part of the ballasted railway track during the service life of FFU sleepers longer than 50 years, a high amount of water can be accumulated around this sleeper that is one of the concerns related to FFU sleepers' application. In addition, sensitivity analyses have been done to unprecedentedly determine the influences of material properties on pull-out capacities. This insight can enable engineers to plan effective, predictive and preventative maintenance activities due to the degradation of railway track components and materials.

Materials and methods

The cubic specimens with holes are extracted from an FFU sleeper factory located in Luoyang city, China (Sunrui 2021). The length, width and height of the cubic specimens are 150 mm, 150 mm and 140 mm, respectively (Fig. 2). Steel screws are fabricated in 38Si7 steel with 235 MPa yield strength. To measure the pull-out strength of screw inside of FFU specimens, two types of a screw which are currently used for FFU railway sleepers in China and 24 standard FFU specimens were manufactured as shown in Table 1. To gain 0.3% water absorption by weight for FFU specimens, they have been placed inside of a water tank for 3 days without screws (Kaewunruen and Tang 2019). Water absorption of FFU specimens is much lower than timber sleepers (>20%), so that after 3 days, tested FFU specimens absorb only 0.3% of water by weight compared with timber counterpart that can absorb water by 19-28% after 1 day (Kaewunruen et al. 2020). The water absorption content is measured according to the ASTM D5229 standard (ASTM 2020). An FFU synthetic sleeper is manufactured using a pultrusion-extrusion technique (Fig. 3). Continuous longitudinal glass-fiber strands are soaked in polyurethane (Fig. 3a & b) curing at a raised temperature and compression shown in Fig. 3c.

Table 1. Properties of FFU specimens considering FFU holes, screw diameters and screw active length.

Specimen ID	Properties			Wet		Dry	
	FFU hole	Screws-(1&2) active length					
	18 mm	80 mm	A	18-AW	18-BW	18-AD	18-BD

20 mm	90 mm 110 mm	B C	20-BW	20-CW	20-BD	20-CD

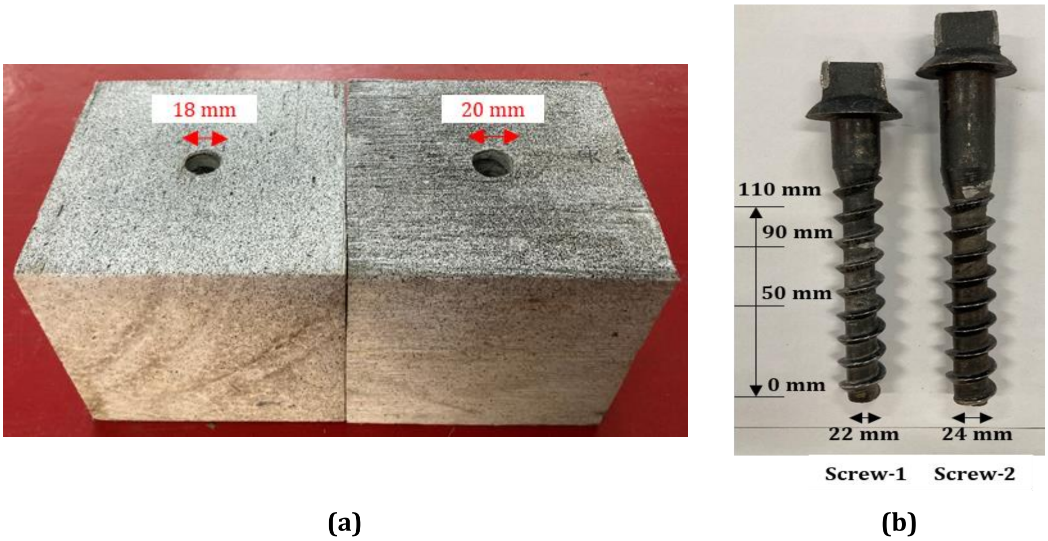


Fig. 2. An overview of **(a)** FFU specimens hole diameter and **(b)** screws length and diameter used in pull-out test of fastening system.

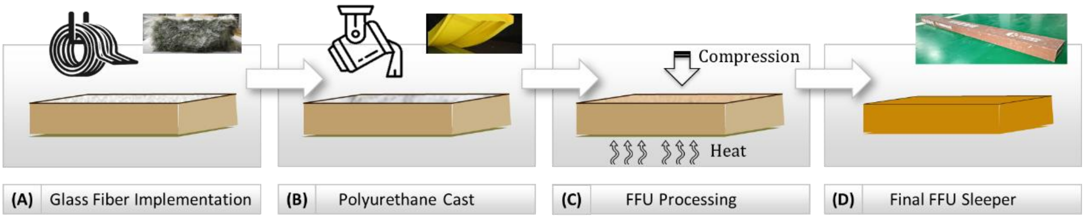


Fig. 3. The manufacturing process of FFU sleepers.

Experimental study

Pull out test

3.1.1. Test setup

Fig. 4 shows the pull-out test equipment. Two loading Jack have been used to provide the pull-out loads. The maximum load of each jack is around 200 kN. The pull-out force has been measured using load cells placed between fixed part and Jacks. The corresponding vertical displacements have been recorded during tests using a linear variable differential transformer (LVDT) with 100 mm measuring capacity. The pull-out test has been performed for both wet and dry specimens in an identical process. Tests are conducted based on DIN EN 13481-2 (Standard 2007-06). The FFU specimens were fixed and then the screws were lifted upward, vertically, by loading jig at a rate of 2 mm/ min until the screw is departed.

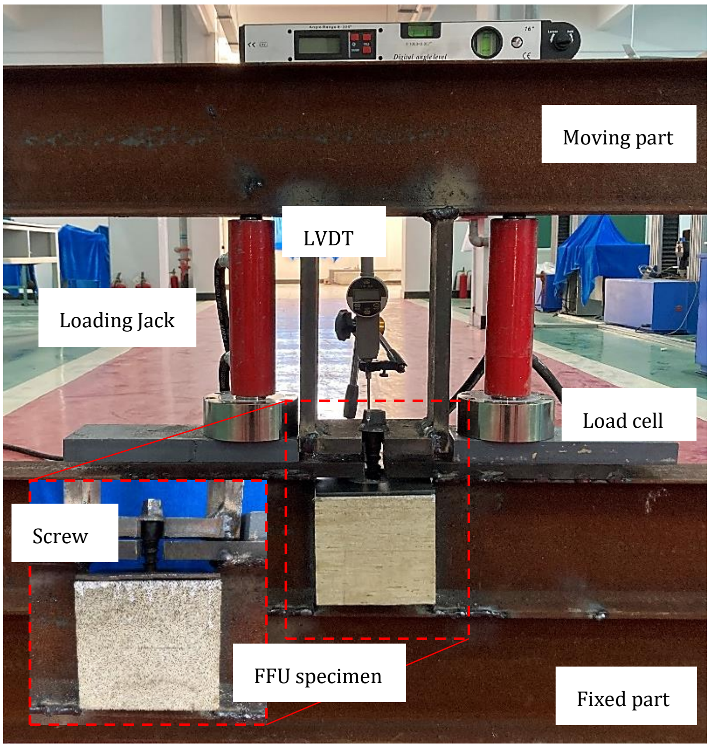


Fig. 4. A test machine layout for pull-out test of FFU specimens.

3.1.2. Pull-out results

Fig. 5 shows the final results of 8 FFU specimens out of 24 tested in this research. Dry specimens show higher pull out strength compared to wet ones. The highest strength belongs to 20-CD with 71.9 kN, which is followed by 20-CW, 20-BD, 18-BD, 18-AD, 20-BW, 18-BW and 18-AW with strengths of 68 kN, 61.7 kN, 59.6 kN and 52.9 kN, 51.3 kN, 44.6 kN and 43.6 kN, respectively. As can be seen, wet specimen of 20-CW with a 20 mm hole and 110 mm screw active length has higher strength rather than other wet specimens as well as its dry state. As expected in Table 2, about 0.3% of water can significantly reduce FFU sleeper strength. So that the strengths of dry and wet specimens of 18-AD and 18-AW, 18-BD and 18-BW, 20-CD and 20-CW, and 20-BD and 20-BW decrease around 18%, 19%, 6% and 13%, respectively. The standard deviation (σ) is calculated for pull-out-test results, as shown in Fig. 5. It is apparent that 20-CD and 20-CW have proportionally higher tensile strengths compared with the standard deviation of all specimens, whilst 18-AW and 18-BW have relatively low strengths.

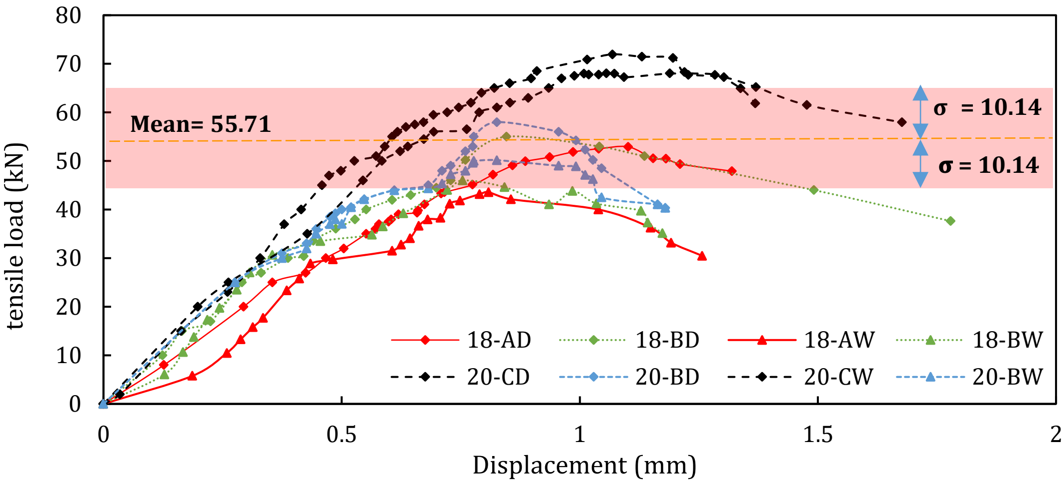


Fig. 5. Pull-out test results based on maximum tensile load of screw and corresponding displacement.

Table 2. A comparison between wet FFU specimens and dry specimens pull out strength.

Specimen ID	18-AD	18-AW	18-BD	18-BW	20-CD	20-CW	20-BD	20-BW
Maximum tensile load (kN)	52.9	43.6	55	44.6	71.9	68	58	51.3
Difference (%)	18		19		6		13	
Average of three specimens (kN)	51.4	42.2	54.7	43.6	70.6	67.6	57.5	50.8
Standard Deviation (kN)	1.12	0.90	0.30	0.65	0.75	0.30	0.60	0.80

Digital image correlation (DIC)

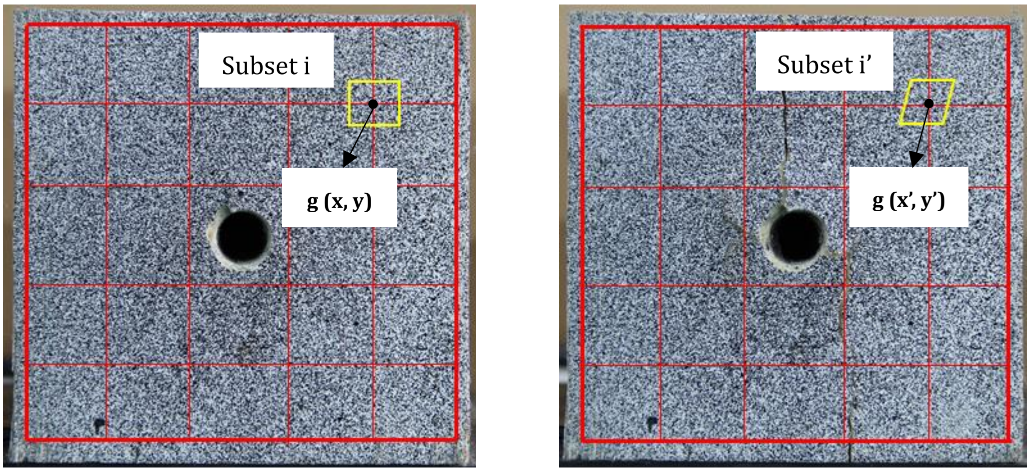
Test setup

There are some limitations to access the surface of FFU specimens during the test due to the pull-out test equipment, digital image correlation (DIC) test has thus been implemented on the intact surface and failed specimens, which is sufficient to capture the crack opening and fracture behavior of FFU specimens. Moreover, some cracks may close after removing the load but the main target of this section is a comparison between residual strain and those cracks which remains visible to compare their openings. Therefore, DIC tests have been carried out for all of the specimens tested in this research. This DIC test has been performed for showing the fracture behavior of FFU specimens due to the pull-out test. The fundamental procedure is comparing the speckle locations before and after loading. The FFU samples potential damage zone is approximately 150 mm× 150 mm. This zone is covered by a speckle pattern which is artificially created by the spray technique so that a layer of white color is spread on the surface of specimens followed by random black spots with a maximum diameter of 0.5 mm. This method was explained in another studies by the authors (Jing et al. 2021; Siahkouhi et al. 2022). Loaded and unloaded surface of FFU specimens are studied using the relationship between the black scale values in the undeformed and deformed states, which represents the initial level of distribution of scale values in the undeformed image (g(x, y)) that becomes g(x’, y’) in the deformed image which can transformed to each other using Eq. 1 and 2.

$$x' = a_1 + a_2x + a_3y + a_4xy \quad (1)$$

$$y' = a_5 + a_6x + a_7y + a_8xy \quad (2)$$

where the a_1 and a_5 values stand for the translation of the center of the subset and the other parameters denote rotation and deformation.



(a) Undeformed specimen **(b)** Deformed specimen

Fig. 6. Schematic presentation of a **(a)** undeformed subset and the corresponding target subset **(b)** after deformation.

This kind of DIC process can reveal the crack deformation before and after pull-out tests. The vision-based measurement system for the estimation of the crack width is composed of a camera with 640 × 480 resolution and software for image acquisition and processing. Therefore, before the test, the specimen has been fixed in the specific place and then after the test they are also located in the same place to take photos for DIC analysis.

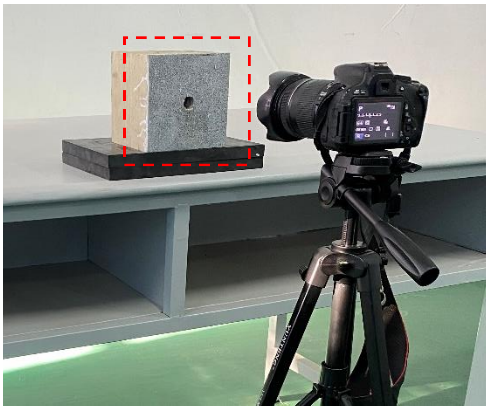


Fig. 7. DIC test setup for capturing images before and after the specimen failure.

Strain maps

To provide a better picture of the propagation of the cracks, the failure stage of specimens is illustrated in Fig. 8. The results show the concentration of cracks for wet specimens rather than dry specimens. As the water absorption content of specimens increased, the localized strains become more prominent and increase in width, indicating crack propagation. It can be seen that water content leads to concentrating cracks resulting in higher crack openings.

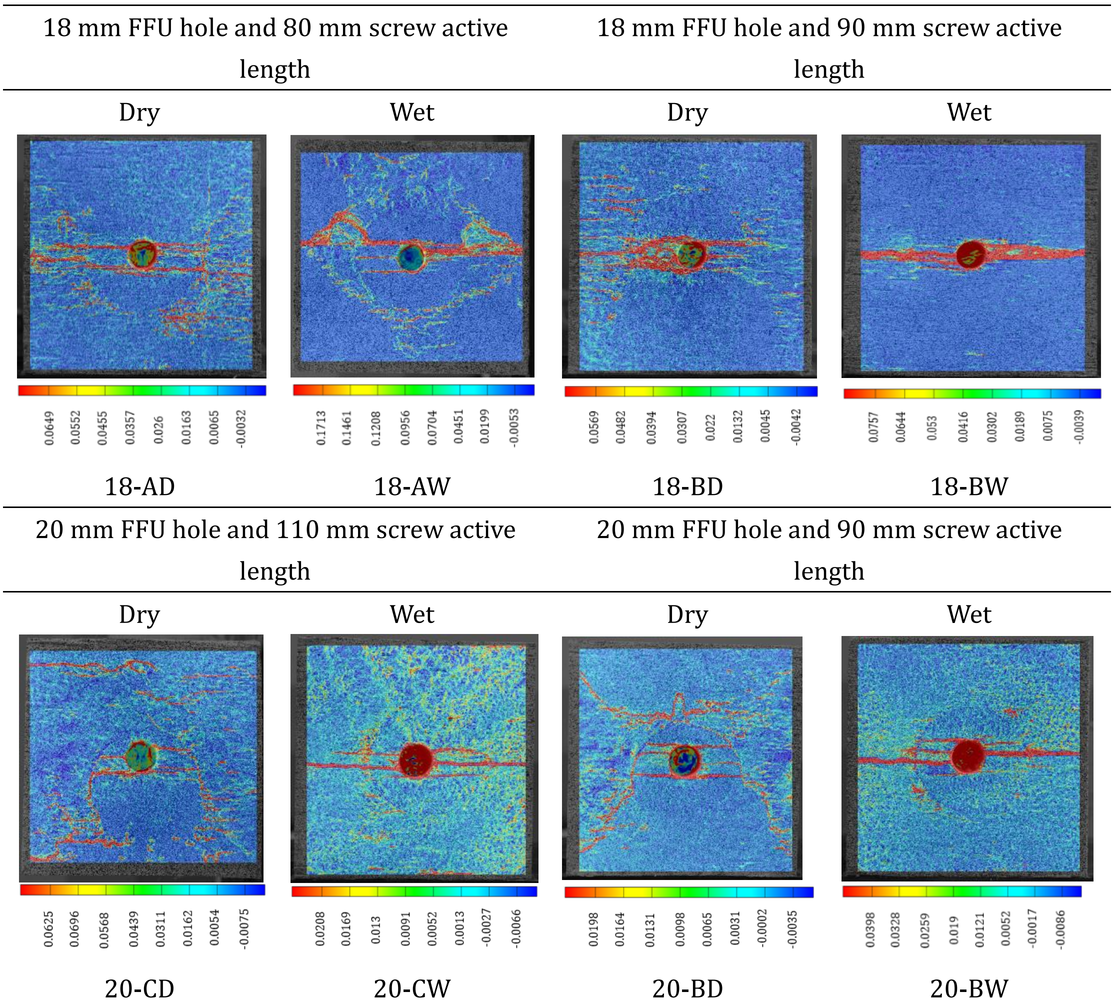


Fig. 8. Crack pattern and crack strains (%) for wet and dry FFU specimens.

Crack mouth opening displacement (CMOD)

There are several cracks on the surface of FFU specimens, the widest crack mouth opening displacements (CMODs) are reported using DIC test results. The failed specimens show more dominant cracks for wet specimens. The widest displacement of crack mouth opening is chosen as the main one in those specimens which have higher tensile loads and are reported in Fig. 9. It is shown that wet specimens have a higher crack opening so that 18-AW, 18-BW, 20-BW and 20-CW have crack openings almost 44%, 27%, 47% and 58% higher than 18-AD 18-BD, 20-BD and 20-CD, respectively. While, in the dry state of the test, 18-BD has a CMOD of 1.03 mm which is followed by 0.84 mm, 0.63 mm and 0.25 mm of 18-AD, 20-BD and 20-CD. In the wet condition, 18-AW shows higher CMOD with 1.5 mm and 20-CW shows the lowest value as 0.6 mm.

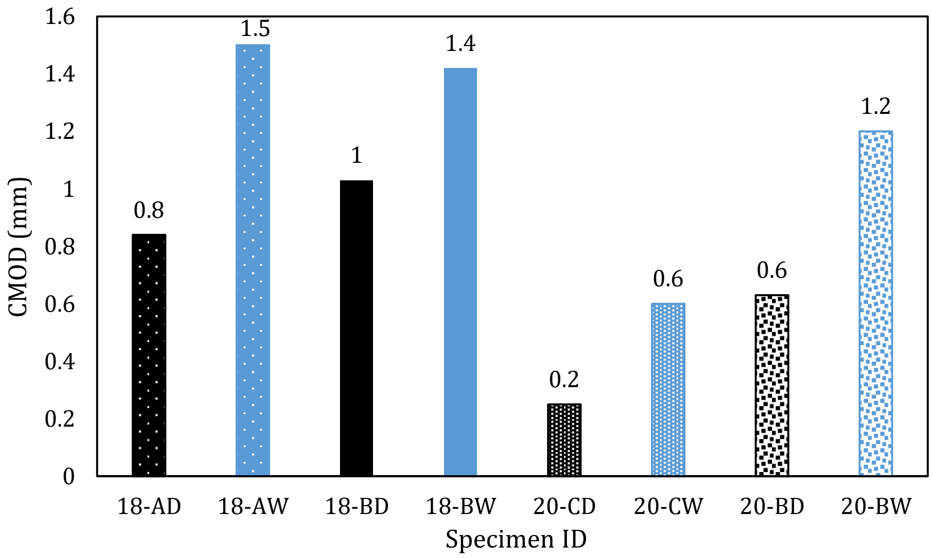


Fig. 9. The maximum CMOD of each FFU specimen after failure.

Results and discussion

Fig. 9 shows that some of the grooves inside of FFU specimens are crushed due to the pull-out forces. Those wet specimens have more crushed grooves that show more failure. In wet specimens, almost the whole length of grooves is crushed, excluding 20-CD. But in the dry state of specimens, the lower section of grooves is mostly crushed. Generally, a 20 mm specimen hole shows better performance rather than an 18 mm specimen hole, moreover, in 20 mm hole specimens, the 110 mm length of the screw has a better performance compared to 90 mm. It should be mentioned that all of 24 specimens show the same behavior, although just 8 specimens are shown in Fig. 10.

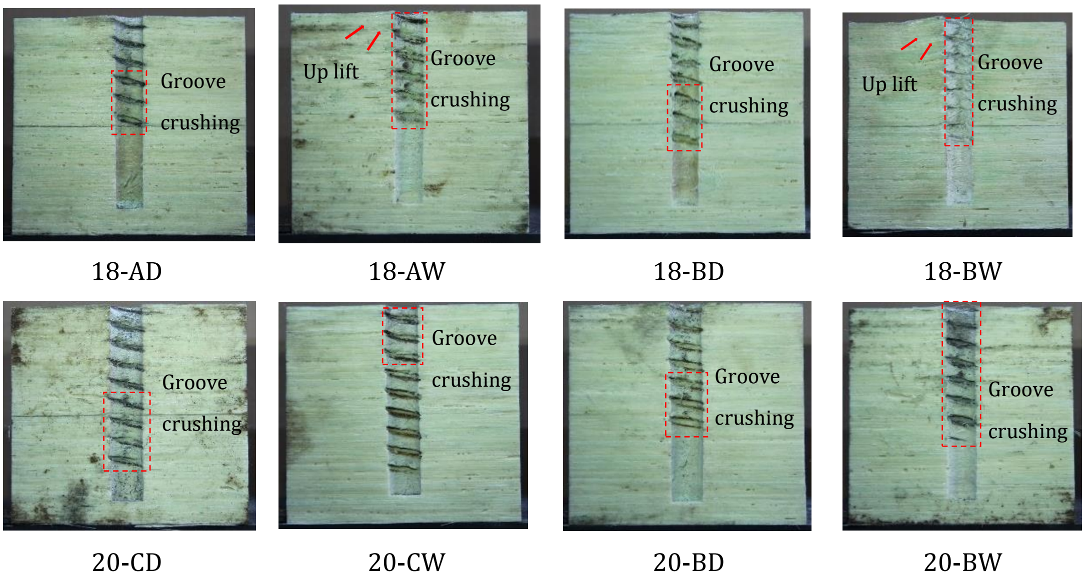


Fig. 10. Sections of FFU specimens after failure.

According to Fig. 7, the identical fracture pattern of wet FFU specimens represents that absorbed water results in the concentration of strains in wet specimens. These wide cracks can be due to the uplift of wet specimens initiated by crushed grooves and the vertical movement of horizontal fibers. The presence of water can lose the placement of the horizontal fibers where the fracture can commence. Dimension of specimens cannot influence test results as the strain concentration happens nearby the hole.

Numerical modeling

Model development

To determine the stress concentration and propagation on the FFU specimens, a 2D numerical model is developed. The FEM model of FFU specimens can be seen in Fig. 11. Modeling components are modeled using deformable solids. The Hex mesh is chosen for the discretization of both the FFU specimen and screws. The mesh size of the FFU specimen and screws are 1 mm. A mesh size sensitivity analysis is performed to check if the finer mesh size effects the final results of stress levels (Esmaeili and Siahkouhi 2019; Jing et al. 2020). The model is an axisymmetric 2D model which contains a half of the real specimen. The properties of FFU specimens are provided by the company catalogue (Sunrui 2021) as shown in Table 3. A tensile static load is applied to the screw. The FFU specimens are completely fixed identical to the experimental test for boundary condition definition.

The FEM for dry specimen has been validated against both company parameters and experimental results. However, there is no data for wet specimens in case of density and young modulus. In this regard, densities are calculated using the ASTM method by dividing mass per volume of specimens. To obtain the wet young modulus of specimens, the validated method is used. Thus, by changing young modulus, the pull-out results are qualified with experimental results of wet specimens. The young modulus of dry specimen has been decreased to the value that the load-displacement graph of wet specimens with different screw and hole diameters are qualified with experimental results. For all of the wet specimens their young modules have almost 3-4% difference with dry young modulus provided by company. These values are identical in the plastic zone of specimens as well, because plastic behavior of materials is less effected by young modulus and mostly are related to yield stress and strain (Chaudhari and Chakrabarti 2012).

Densities of wet specimens calculated using ASTM D5229 standard (ASTM 2020), which have a little difference of almost 0.4% with Dry state of specimens.

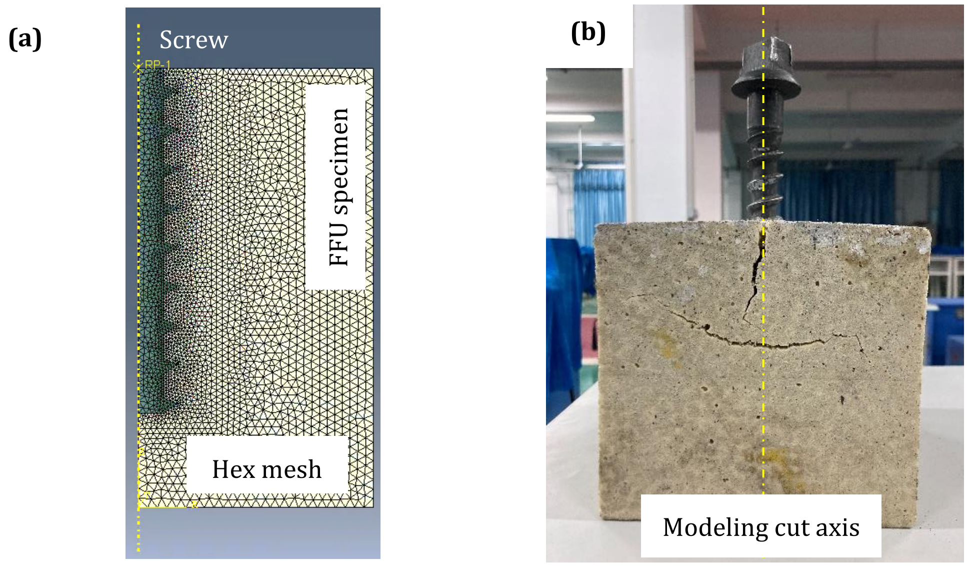


Fig. 11. An overview of **(a)** FEM model compared to **(b)** the FFU specimen with screw.

Table 3. The properties of FFU specimens and Screw used in FEM.

Materials		Density	Young modulus	Poison's ratio
		kg/m³	MPa	
FFU specimen	Wet	743	1005	0.3
	Dry	740	1045	
Steel screw		7850	210000	0.27

Model validation

In order to validate the developed FEM model of pull out test, the load-displacement curve has been used for the wet and dry FFU specimens. The same validation process has been adopted as in Refs. (Jing et al. 2021; Jing et al. 2020). As observed in Fig. 12, the FEM and experimental results show an excellent agreement. The maximum discrepancies between experimental and numerical results of pull out tests of 18-AD, 18-AW, 18-BD, 18-BW, 20-CD, 20-CW, 20-BD and 20-BW are 1.7%, 1.5%, 0.5%, 0.8%, 1.7%, 2%, 0.17% and 0.09%, respectively, which are less than 2% difference leading to a validated model (Table 4).

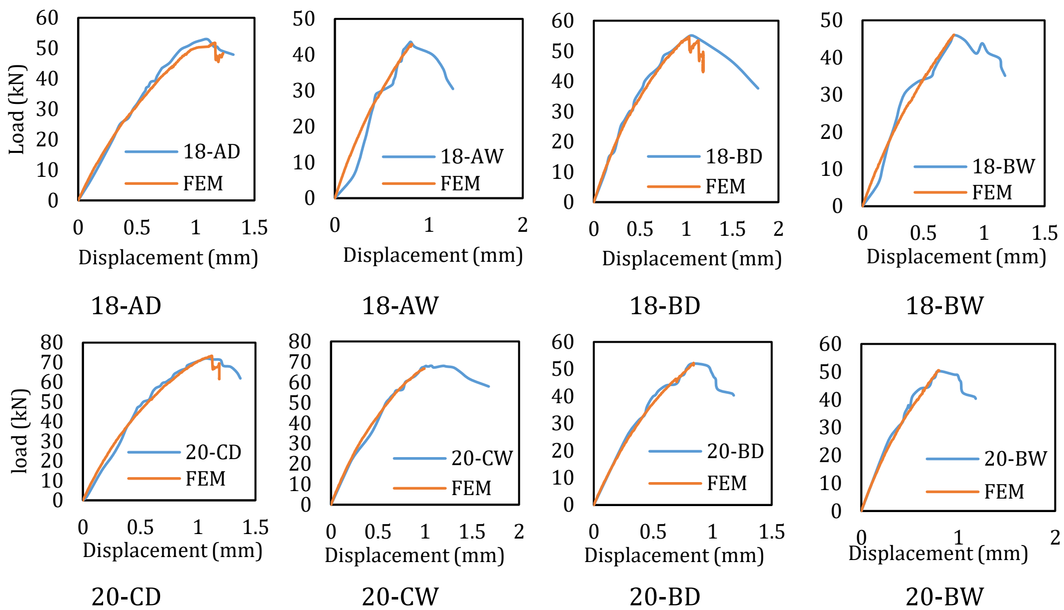


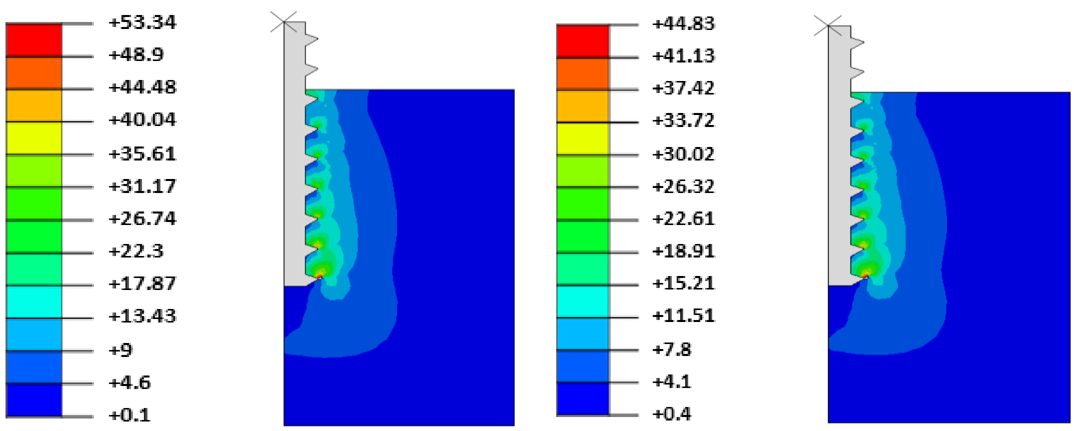
Fig. 12. Validation graph for experimental test results and FEM.

Table 4. The difference between maximum pull-out test load for experimental and FEM results.

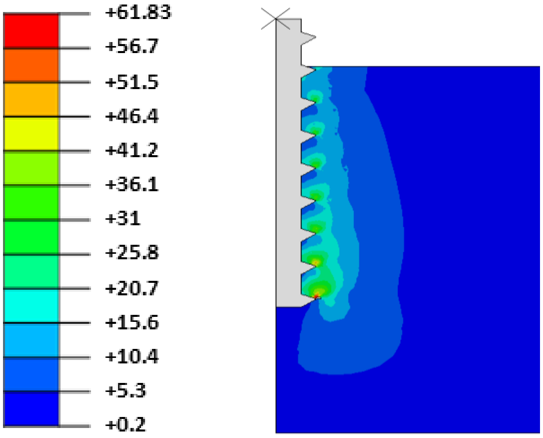
Specimens		18-AD	18-AW	18-BD	18-BW	20-CD	20-CW	20-BD	20-BW
Pull-out load (kN)	FEM	52	42.9	54.7	46.1	73.2	66.6	52.2	50.3
	Exp.	52.9	43.6	55	46.1	71.9	68	52.1	50.2
Difference (%)		1.7	1.5	0.5	0.8	1.7	2	0.2	0.09

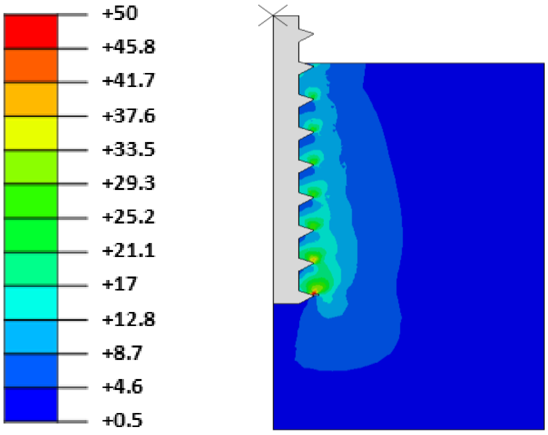
Parametric studies

After the validation of the FEM model, the von Mises stresses of both wet and dry specimens are separately measured and reported in Fig. 13 and Table 5. The von Mises stresses of all FFU specimens are measured and compared with different screw and hole diameters. Due to tensile stresses which occur in the specimens, the von Mises stress is used as a criterion to determine whether specimens reach a yielding limit. Most of cracks initiate in the zones with the highest stress accumulation (Diederichs et al. 2004). To find these zones and compare stress levels of specimens an elastic behavior study of specimens is enough. It is concluded that the maximum stress in the dry specimens is greater than wet specimens. In addition, the maximum difference value between corresponding dry and wet specimens belongs to 20-CD and 20-CW because they have a higher pulling load compatible with the experimental tests. 20-BD and 20-BW show the lowest amount of difference between stress levels by 14% in wet and dry specimens which are followed by 18-AD and 18-AW, 18-BD and 18-BW, and 20-CD and 20-CW with 17%, 18%, and 36%, respectively. Fig. 14 presents von Mises stress development for FFU specimens of 25%, 50%, 75% and 100% of failure load. It can be concluded that there is no abnormal behavior such as a sharp increase in stresses after 75% failure load to 100% failure load between wet and dry specimens, excluding 18-AD and 18-AW. In these two specimens, although 18-AW has higher stress by 25%, 50% and 75% of total load, the final failure load (100%) generates lower stress compared to 18-AD. It can be due to the lower final strength of 18-AW rather than 18-AD. The 20-CD specimen shows a significant increase in stress from 75% to 100% failure load that shows the higher final strength of this specimen against tensile load.

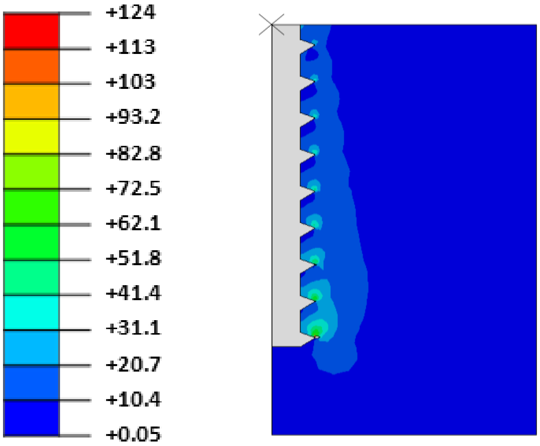


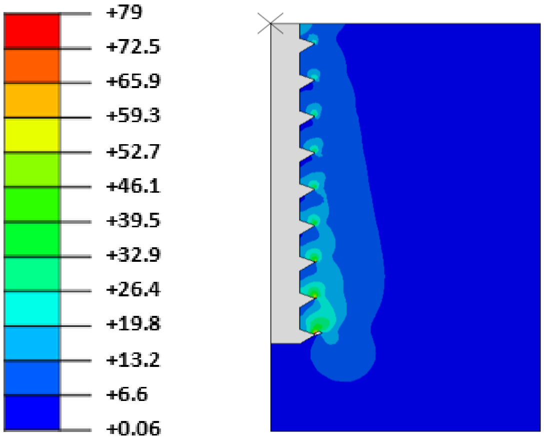
18-AD 18-AW



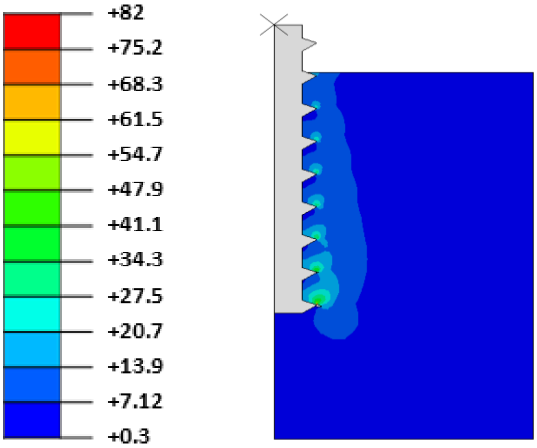


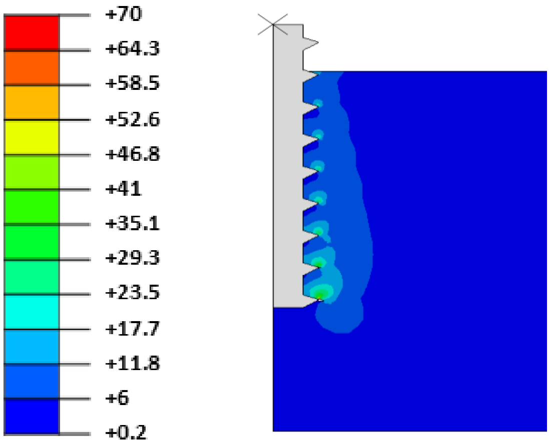
18-BD 18-BW





20-CD 20-CW





20-BD 20-BW

Fig. 13. Von misses stress distribution contours (MPa) of FFU specimens in pull-out test simulation.

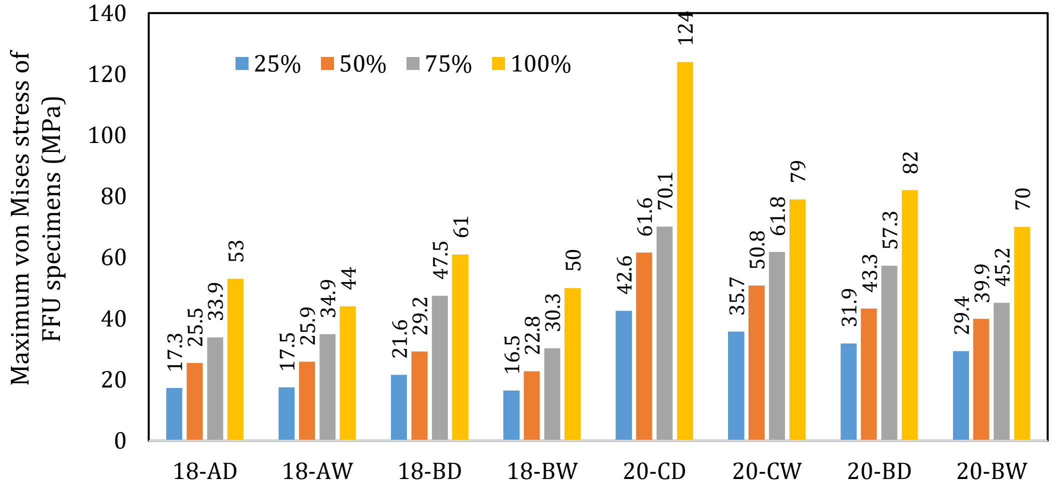


Fig. 14. Von Misses stress of FFU specimens in 25%, 50% and 75% of failure load.

Table 5. The difference between maximum von Mises stresses between wet and dry specimens in FEM.

Specimens	18-AD	18-AW	18-BD	18-BW	20-CD	20-CW	20-BD	20-BW
Stress ($\sigma_{\max S}$) (MPa)	53	44	61	50	124	79	82	70
Difference (%)	17		18		36		14	

Sensitivity analysis on the elastic modulus reduction

As seen, 4% reduction in elastic modulus and 0.4% increase in density of FFU specimens due to 0.3% absorbed water result in a change in pull-out loads. Therefore, a sensitivity analysis has been done to measure the amount of pull out resistance of FFU specimen after changing their elastic modulus (E) and density (D). E and D of FFU specimens in FEM change corresponding to two different modeling groups (I & II) as shown in Table 6. In these two different modeling groups, different types of FFU composite sleepers are included to measure the influence of the two main parameters E and D with FEM.

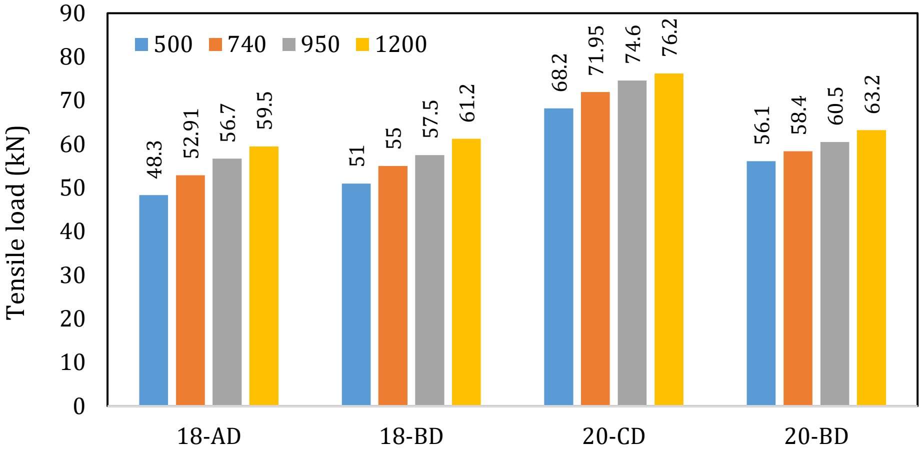
Table 6. The different properties of FFU specimens in FEM.

Modeling groups	Properties	Values

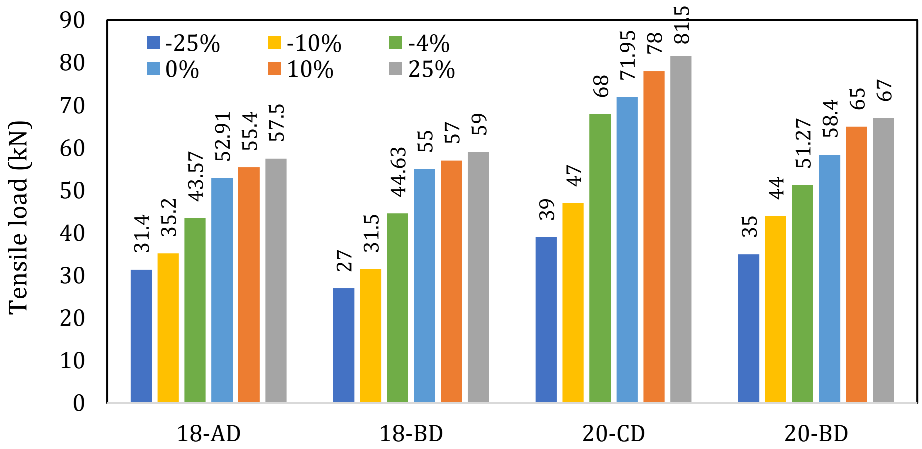
Group I	Density (kg/m^3)	500	740	950	1200
	Elastic modulus values (MPa)	1045			
Group II	Density (kg/m^3)	740			
	Elastic modulus values (MPa)	784	940	1149	1306

Fig. 15a presents the influences of changing density of FFU sleeper with values by 500 kg/m^3, 740 kg/m^3, 950 kg/m^3 and 1200 kg/m^3. It can be concluded that higher density increases tensile strength. 18-AD specimen with 500 kg/m^3 density has the lowest tensile strength as 48.3 kN, while 20-CD with 1200 kg/m^3 density has the highest one as 76.2 kN.

Fig. 15b shows that increasing elastic modulus enlarge tensile strength of specimens, while, reducing elastic modulus decline FFU specimens tensile strengths. According to four new values of elastic modulus as 783.75 MPa, 940.5 MPa, 1149.5 MPa and 1306.25 MPa, it can be concluded that increasing elastic modulus has less effect on tensile loads than decreasing them, as can be seen, 18-AD, 18-BD, 20-CD, and 20-BD specimens with almost 25% increase in elastic modulus to 1306.25 MPa have +7%, +7%, +13% and +14% higher tensile strength, respectively, while, for almost -25% reduction in elastic modulus to 783.75, the tensile strengths decrease by -40%, -50%, -45% and -40% percentages, respectively. The same trend is followed for other elastic modules.



(a)



(b)

Fig. 15. Tensile load results from pull-out test of FEM model with different **(a)** densities and **(b)** elastic modulus.

Conclusions

This study aims to evaluate the influences of wet and dry conditions, sleeper drilled hole diameter, and screw active length inside of sleeper on the pull-out resistance of FFU sleeper fastening systems. DIC tests have been performed to evaluate the fracture on the surface of FFU specimens. In addition, a numerical model has been established and validated in order to determine the stress level of the FFU specimens under the pull-out action. The experimental test results demonstrate that only 0.3% of water absorption can significantly influence the

FFU sleeper performance. This research offers proof of concept and new evidence; and more research is needed to verify the repeatability of the test results, and obtain conclusive evidence, which will be presented in the future. However it is important to note that FFU material complies with ISO9000 series, and the repeatability has been validated in the factory (unlike granular materials or soils). Our tests fully comply with all test standards for sleepers (in terms of material samplings and the number of specimens required). The major experimental and numerical findings are categorized as follows:

1. The highest pull out strengths in dry and wet states belong to the specimen with 20 mm hole and 110 mm active length of the screw inside of the specimen, with strengths of 71.95 kN and 68 kN, respectively.
2. It is shown that wet specimens have a larger crack opening so that the wet specimen with an 18 mm hole and 80 mm screw active length has the widest crack mouth opening displacement as 1.5 mm.
3. According to FEM results, dry and wet specimens with 20 mm hole and 110 mm screw active length show the highest amount of difference between dry and wet states stress levels.
4. Considering experimental and FEM results, it can be concluded that 20 mm FFU hole with 110 mm active length of a 24 mm thickness screw is the best option for FFU sleepers fastening system, especially in a wet condition with a high rate of water absorption potential.
5. Changing elastic modulus and densities of FFU specimens show that specimen

with 20 mm hole and 110 mm screw active length still have the maximum performance even in lower values of elastic modulus and density. Reducing elastic modulus and density of FFU specimens decrease pull-out resistance.

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Data availability statement

Some or all data, models, or code that support the findings of this study are available from the corresponding author upon reasonable request.

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