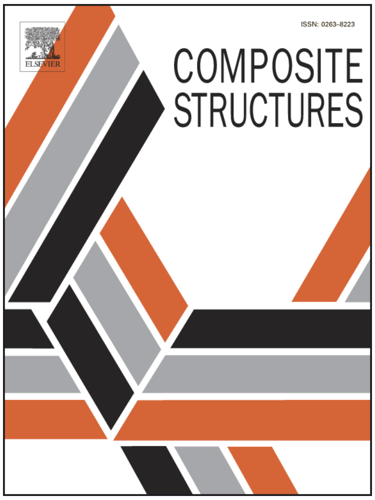

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A novel strong and durable near-surface mounted (NSM) FRP method with cost-effective fillers

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Abstract

Conventional near-surface mounted (NSM) FRP methods rely on expensive and less durable epoxy-filler bond to transfer tensile force from FRP reinforcements into concrete elements, generally failing to fully develop the tensile strength of FRP reinforcements. In this paper, cost-effective and potentially more durable fillers (e.g. cement-based paste and ceramic tile adhesive) combined with anchorages have been proposed to improve conventional NSM FRP methods. Experimental results demonstrate that the proposed NSM methods are able to make full use of FRP reinforcements, suggesting excellent compatibility between fillers and the proposed method. Further mechanical improvements can be achieved by evenly distributing the FRP material of one groove into multiple grooves. Moreover, the study tends to use high-viscosity cement filler for facilitating FRP installation especially on the bottom or side of concrete elements. The application of flexural reinforcement on the side of concrete elements have also been explored, aiming to deliver a much easier FRP installation. It is believed that the paper presents feasible improvements for NSM methods. Test results suggest that those improvements can achieve a stronger and potentially more durable NSM method with cost-effective fillers.

Keywords: NSM FRP methods; Epoxy filler; Cement-based paste; Anchorage; High viscosity; Multiple grooves; Full use

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1. Introduction

FRP composites have potential for strengthening concrete structures[1–8]. Generally, externally bonded (EB) are used for shear/flexural strengthening of concrete structures[9,10]. Alternatively, concrete structures can be strengthened by embedding FRPs into the near surface of concrete elements and then covered by bond filler (e.g. epoxy resin, cement, etc.). This is near-surface mounted (NSM) methods [11–13] which have several advantages over conventional EB methods. For example, NSM methods tend to deliver greater bond condition than that of EB FRPs [14–17]. Embedded FRP composites are also better protected against fire [18], harsh environment and mechanical damages [19], suggesting greater sustainability.

Conventional NSM methods rely on either epoxy-based or cement-based bond to transfer tensile force from reinforcements to concrete matrix. When epoxy resin is used, it tends to deliver much stronger FRP-concrete bond than that of comparable cement grout [20]. Nevertheless, many engineers still favor cement grouts because they are much cheaper. For example, in general, cement costs ¥ 350-¥ 500 per ton in China. Comparably, the cost of epoxy for curing CFRP materials could be as high as hundreds RMB per kilogram. Moreover, cement has better durable performance against freeze and thaw cycles than that of epoxy-based bond [20–22], and high-viscosity cement paste can be readily achieved by controlling the water-binder ratio [23], allowing a much more easily application to cover FRP embedment at the positive moment (i.e. the bottom of elements) or shear regions (i.e. the sides of elements). On the other hand, liquid epoxy resin is considered as an effective bond material primarily for those strengthening applications at the negative moment regions (i.e. the top of elements) [24].

Furthermore, existing NSM methods also suffer from premature failures because of either FRP debonding [25] or the separation of concrete cover (i.e. concrete rupture) [26]. NSM FRPs could be embedded into an adjacent concrete component to effectively delay the premature failures [25,27]. Furthermore, H-shape FRPs were manually fabricated to resist debonding failures [28]. Complicated mechanical anchorages have also been developed for anchoring prestressed NSM FRP reinforcements [29]. Although those studies provide with promising candidates, current NSM FRPs cannot be easily anchored as that of conventional steel reinforcements. Probably, current NSM methods prefer to use commercial thermoset FRP bars which are incapable of being bent into effective anchorages in field [30,31], limiting their potentials to be effectively anchored. Recently, a novel anchored NSM FRP reinforcement has been developed by the authors of the present paper to more readily and effectively prevent the premature failures of both FRP bebonding and concrete rupture [32]. The anchored NSM reinforcement is made by FRP sheets. By using the flexible characteristic of FRP sheets before curing, effective anchorages can be easily fabricated as the bent parts of the reinforcement. The bent anchorage will continue transferring the tensile force from reinforcements to concrete after debonding occurs. Comparably, conventional FRP reinforcements are considered as thermoset elements which cannot be bent after curing. Therefore, a larger bond length is required to fully develop the tensile strength of FRP reinforcements. Experimental results obtained from bending tests demonstrated that the proposed method was capable of fully developing the tensile strength of FRP reinforcements with minimum bond contribution. Provided the introduction of anchorages compromised the load transferring contribution of epoxy bond [32], cost-effective fillers e.g. cement-based paste and ceramic tile adhesive could deliver comparably capacity to that of conventional epoxy-based method. Furthermore, less environmental-sensitivity fillers e.g. cement-based paste and ceramic tile are able to achieve better protections against UV light and freeze and thaw cycles [20–22]. By controlling the water-binder ratio, the selected filler materials can be well prepared as high-viscosity fillers, facilitating their applications for those regions generally inhibiting to hold liquid epoxy resin (e.g. positive moment and shear regions). It should be noted that the performance of the proposed fillers depends on installation quality, and the compatibility between cost-effective fillers and the proposed methods have not been experimentally evaluated yet.

In this study, experiments have been prepared to demonstrate the merits of the proposed NSM method with cost-effective fillers. Results suggest that the tests using the cost-effective and potentially more durable fillers can achieve larger strength that that of conventional NSM methods with epoxy filler, and deliver as high strength as that of comparable experiments with epoxy filler. The high-viscosity fillers can also be easily installed for those side/bottom-applications. It is therefore believed that this study is not only a bridge for epoxy-filler and no-filler studies [32] but also presents valuable pioneer explorations in usage of cost-effective and potentially more durable filler to achieve a stronger and easier-installation NSM FRP method than that of existing ones.

2. Experimental program

2.1 Test setup and specimens

In this study, three-point flexural tests (based on ASTM C293 [33]) have been used to develop tensile force on FRP reinforcements (see Fig. 1), which were designed as the solo tensile-force-carrying elements of pure concrete blocks with a size of 610 (length) mm×152 (width) mm ×152 (depth) mm and no reinforcements (see Fig. 2). As shown in Fig. 2, grooves with a constant dimension of 444 (length) mm×30 (width) mm×16 (depth) mm were pre-excavated either conventionally into the tensile surface or innovatively into the side of pure concrete for installing FRP reinforcements. The groove dimensions were determined by the resultant size of FRP reinforcement and the groove design recommendation in literature [24][32]. Compared with the conventional application into the bottom of elements, side embedment provides a competitive alternative for excavation at a comfortable working height and readily holding filler to form bond with the present of bottom boundary layers. By using the proposed anchorage technique to realize the full strength of FRP reinforcements, high-viscosity cement-based fillers can be applied to readily seal the side groove which is a quite challenge for existing NSM methods and might compromise the bond condition. Holes are pre-drilled to install the 85 mm-depth FRP embedment, i.e. the bent FRP anchor. The hole centers are 18 mm away from the groove end [32]. In order to ensure a desired cracking path, a 25 mm-depth cut has been prepared at the midspan [34]. The shear capacity of the concrete blocks has been strengthened by two separated FRP U-wraps, which have no physical connection with each other, providing limited tensile contribution for the concrete blocks as shown in Fig. 2. The concrete compressive strength f_{cu} was experimentally determined as 36 MPa, which was an average value of six compression tests on concrete cube (150 mm×150 mm×150 mm). All FRP components were made by unidirectional and dry Tyfo® SCH 11-UP strips with manufacturer provided Young's modulus E_f of 95.8 GPa, ultimate stress of 986 MPa and strip thickness of 0.5 mm [35]. The same epoxy was used to make FRP reinforcements and fill grooves. The manufacturer provided tensile modulus, tensile strength and elongation percent of this epoxy at the curing schedule 72 hours are 3.18 GPa, 72.4 MPa and 5.0%, respectively. The compression strength of cement-based paste at the 28th day is 32 MPa with a mixing ratio of 1 cement: 3 sand: 0.6 water, and the manufacturer (Oriental Yuhong C200) provided shear strength of the ceramic tile adhesive is 1 MPa [36]. All specimens have been cured and tested in room temperature to minimize the environmental impact.

Those flexural tests were loaded with a slow stroke rate of 0.3 mm/min to gradually deliver tensile force to FRP reinforcements. Provided the brittle characteristic of FRP material would result in unpredictable critical section for the fracture failure, strain gauges might not be preset on the section to capture the representational value standing for the maximum deformation of reinforcements. The embedded reality also inhibited the usage of digital image correlation (DIC) system to measure reinforcement deformation. Instead, the behavior of FRP reinforcements was determined by the equilibrium at the ultimate load P_u. In this equilibrium, the maximum tensile force was equal to the corresponding compressive force introduced in concrete, and the bending moment was balanced by the relative internal resistance of concrete and reinforcement. The introduction of the equilibrium has been elaborated in the literature [32], and therefore will not repeat in this paper. Applied loads were measured by the load cell of the compression testing machine CSS-WAW1000DL. The midspan deflection was obtained from the relative DIC measurements at the midspan and two ends as shown in Fig. 1.

2.2 Fabrication and installation of FRP reinforcement

Fabrication and installation are the keys to achieve desired capacity. In this study, FRP reinforcements were made by folding either one 127-mm-wide FRP strips for one-groove applications or two 64-mm-wide FRP strips for two-groove applications. This arrangement tended to deliver comparable specimens with equivalent amounts of FRP materials used for flexural reinforcements. As shown in Fig. 3 (a), those strips were first saturated with epoxy resin. Then, they were widthwise folded either thrice for 127-mm-wide strips or twice for 64-mm-wide strips, resulting in corresponding 16 mm ×4 mm and 16 mm ×2 mm sections respectively. The reinforcement lengths were 440 mm for the conventional NSM method without anchorage and 948 mm for the anchored NSM applications including one 208 mm reinforcement, two 85 mm lengthwise folded embedment, and two 100 mm overlaps (see Fig. 3 (b)). More geometrical details can be found in the literature [32]. Grooves and holes were well cleaned by using compressed air and then saturated for FRP installation. Steel sticks were used to help inserting FRP reinforcements into the pre-drilled holes. The amount of FRP material was doubled in the embedment and the 100 mm overlap to strengthen the anchorage region. Then, epoxy resin would be used to fill holes and grooves, forming a typical FRP-concrete bond. Alternatively, epoxy resin was used to fill holes only and then attach FRP reinforcements on the groove surface. Those grooves were filled with cement-based paste/ceramic tile adhesive after curing epoxy resin for one day. The one more curing day was used to form a solid epoxy-based matrix for FRP reinforcements, minimizing any negative impact that might be introduced by cement-based paste/ceramic tile adhesive. As shown in Fig. 3 (c), those cement-based paste and ceramic tile adhesive were deliberately made as high-viscosity fillers to facilitate their applications on the side and bottom of concrete elements. All specimens were tested after the 28th day of installation which allowed all kinds of bond to reach their desired strengths.

2.3 Variables

In this study, adequate anchorage systems combined with cement-based paste/ceramic tile adhesive were used to deliver a stronger, cost-effective and durable NSM method than that of conventional epoxy-based NSM methods. This method is expected to bridge the gap between the studies of the anchored NSM method with/without epoxy fillers[32]. In order to demonstrate the merits of the proposed NSM method, experimental comparisons have been made for those specimens strengthened with various NSM methods, i.e. anchored/unanchored methods, different fillers (i.e. epoxy-based filler, no filler, cement-based paste and ceramic tile adhesive), one/two/side-groove applications (see Table 1). Specimen No. 1-21 are selected from literature [32] to evaluate the performance of comparably cost-effective method No. 22-33. It should be noted that the same amount of flexural FRP material has constantly been either applied for one-groove applications or evenly distributed into two/side-groove application to achieve comparable experimental results.

First of all, tests are prepared to demonstrate the performance of specimens using epoxy-based filler (EF). They are anchor-free (AF) NSM tests, anchored (A) NSM tests with epoxy-based filler and anchored NSM tests with no filler (NF). Since several small anchorages can carry larger tensile forces than that of a big anchorage with equivalent FRP material [37], two-groove (2G) and side-groove (SG) applications have also been prepared. Moreover, excavating grooves and installing FRP reinforcement on the sides of concrete elements are expected to be much easier than that of comparable installations on the bottom. Then, comparable groups of tests using either cement-based filler (CF) or ceramic tile adhesive (CA) for those one-groove application (1G), two-groove (2G) and side-groove (SG) applications have also been conducted. The labeling system introduced in this study is anchorage condition (AF and A)-filler condition (NF, EF, CF and CA)-groove condition (1G, 2G and SG)-unique ID (a, b and c).

3. Results and discussion

Based on 33 experiments with various anchorage types, different filler materials and groove condition, the potentials of the anchored NSM method with cost-effective and potentially more durable fillers are explored in this section.

3.1 NSM method with epoxy-based filler or no filler

Nine tests are selected to present the impact of anchorage and epoxy-based filler. The first three tests (No. 1-3) are selected to represent the performance of the conventional epoxy-based NSM method without any anchorage application. Test No. 4-6 are prepared to demonstrate the direct improvement brought by the anchorage system. The direct impact of epoxy-based fillers are presented by another three anchored tests with no filler (No. 7-9).

Fig. 4 illustrates the load-deflection curves of those selected experiments. It can be seen that those tests using epoxy-based filler (No. 1-6, i.e. AF-EF-1G and A-EF-1G) tends to deliver quite equivalent load-deflection stiffness in both pre-crack and post-crack stages. Without any epoxy filler, only one out of three anchored NSM test (No. 7-9, i.e. A-NF-1G) developed comparable post-crack load-deflection stiffness with that of those epoxy-based tests. Tests using the conventional NSM method without anchorages (No. 1-3) eventually failed in concrete rupture (see Fig. 5 (a)). All anchored NSM tests with epoxy-based filler (No. 4-6) failed in FRP rupture (see Fig. 5 (b)), delivering 22%-83% larger ultimate loads than that of those conventional NSM tests (No. 1-3). Relying exclusively on anchorage without any epoxy filler, however, anchors (No. 7-9) can be prematurely pulled out (see Fig. 5 (c)) at less predictable loads. With an adequate filler (e.g. epoxy or cement), epoxy-based and cement-based test No. 4-6 & 10-12 developed comparable and much stable ultimate loads which are notably larger than that of the conventional method with epoxy filler. This suggests the critical contribution of filler on transferring force to reach the desired strength. Nevertheless, inherent variability in terms of material, construction and testing variability makes some tests to have slightly larger ultimate loads than equivalent others.

Those observation suggests the effect of filler, which could not only help transferring tensile force from reinforcements into anchors but also well distribute tensile force into the concrete bonded with reinforcement. On the other hand, the introduction of anchorages helps to make fuller usage of FRP reinforcement, preventing undesired concrete failure or FRP delamination [32]. Thus, fillers can be used to improve both strength and stiffness as well as prevent undesired failure. In light of those observations, comprehensive explorations combining anchorages with cost-effective and potentially more durable fillers are presented and discussed in the following section.

3.2 Comparable NSM methods with cheaper fillers

In order to identify more competitive filler replacements, another six tests with cheaper fillers, i.e. cement-based paste (No. 10-12) or ceramic tile adhesive (No. 13-15), have been conducted. Their performances are compared with their relative tests with epoxy-based filler (No. 1-6) or no filler (No. 7-9) and then discussed in this section.

First of all, it was found that the installation in usage of high-viscosity fillers, i.e. cement-based paste and ceramic tile adhesive, was much easier than comparable installations using epoxy-based filler. The cement-based paste with a mixing ratio of 1 cement: 3 sand: 0.6 water could be readily used for bottom or side application with few additional preparations or supports. As shown in Fig. 6, the typical failure modes of tests using cement-based paste and ceramic tile adhesive are FRP rupture and anchor pull out, respectively. All tests using cement-based paste developed desired ultimate stresses (see Table 2) which were not less than the rupture value (986 MPa) provided by manufacturer. On the other hand, however, tests filled with ceramic tile adhesive failed to fully develop the tensile strength of FRP reinforcements although they delivered comparable ultimate loads to those conventional NSM tests (No. 1-3) without using anchorages. Those observations suggest that cement-based filler can well work with the proposed anchorage system to make full use of FRP reinforcements, and ceramic tile adhesive might not be an adequate candidate for this NSM method requiring few further explorations.

Fig. 7 illustrates the load-deflection comparisons between cheaper-filler tests and typical epoxy-based tests with/without anchorages (i.e. A-EF-1G-b/ A-EF-1G-c). Both figures show that those cheaper-filler tests tend to deliver a softer load-deflection behavior after concrete cracking. The observation suggests the effect of filler bond on transferring tensile force. With epoxy-based filler, tensile force can be more effectively transferred, developing less deflection at any given load after concrete cracking. Moreover, epoxy-based tests tend to develop larger ultimate loads than that of comparable tests using cheaper fillers. This might once again suggest that filler could help to transfer more tensile force into concrete, and therefore reduced the apparent force carried by FRP reinforcement resulting in larger ultimate loads.

Moreover, the impact of filler on the ultimate load is clearly shown in Fig.8. The average load at the ultimate of no-filler tests is around 46 kN less than that of those tests using conventional NSM method (51 kN). The introduction of ceramic tile adhesive slightly improves the value to 51 kN. Cement-based filler notably increases the value to 69 kN which is comparable to the average value (78 kN) achieved by those tests using epoxy-based filler. The observations suggest that the proposed NSM method might be not able to deliver desired loading behavior without an adequate filler and cost-effective and potentially more durable cement-based filler can be a promising replacement for epoxy-based filler. In order to further minimize the effect of bond filler, possible improvements have been proposed and discussed in the following section.

3.3 Improvements of anchored NSM methods with cement-based filler

Previous study [38] suggests that FRP reinforcements with smaller cross-section area tends to achieve larger ultimate stresses than that of comparable reinforcements with larger cross-section area. Moreover, it is also found that smaller anchors are more efficient than larger anchors in transferring tensile force [37]. Both of them suggest the possible improvements that can be achieved by evenly distributing the FRP material of one-groove application into multiple-groove applications, e.g. two-groove application and side-groove application.

As shown in Fig. 9, all two-groove tests failed in desired FRP rupture while side-groove experiments developed undesired block failure, suggesting large mid-span deflection that destabilized the equilibrium of the concrete block. The load-deflection comparisons (shown in Fig. 10 (a)) also favor the two-groove application in terms of 1) developing comparable load-deflection stiffness to that of the conventional NSM method and the anchored NSM method with epoxy-based filler, and 2) delivering notably larger ultimate loads standing for 17%-46% improvements compared with that of anchored NSM method with epoxy-based filler. Although installing FRP reinforcements on the side of concrete elements would be much easier applications in field, they failed to fully develop the tensile strength of FRP reinforcement (see Fig. 10 (b) and Table 2). Unlike conventional application into tensile substrate, side-groove applications allow both lateral and vertical slip as shown in Fig. 11. The notably vertical slip would compromise the load-deflection stiffness after concrete cracking, and result in significant midspan deflection destabilizing the concrete specimens. Cement-based and epoxy-based test No 19-21 & 28-30 are able to limit the vertical slip and therefore develop much more convergent and larger loads at ultimate than that of no-filler test 31-33. In the future, more works can be done to inhabit the vertical slip by optimizing groove geometries and/or applying multiple anchorages. Then, the side-groove application would reward us with a more feasible NSM method.

3.4 Promising replacement for epoxy-based filler

Comparisons are made in this section to demonstrate the merits of cement-based filler. This merits includes availability, material cost and durability. First of all, the cement material is widely available with a reasonable price ranging from ¥350-¥500 per ton in China. Comparably, the specific high-quality epoxy is imported from U.S., costing as high as hundreds RMB per kilogram. Secondly, cement-based fillers are considered to have less environmental impacts (e.g. temperature and UV light) than that of epoxy-based fillers [20–22]. Cement-based fillers are therefore expected to have more stable performance during their entire life cycle. Then, various tests have been conducted to identify a reasonable usage of cement-based filler in which cement-based NSM methods are able to achieve comparable performance to that of epoxy-based equivalence.

For the one-groove applications, cement-based tests deliver comparable ultimate loads (av.=69kN) to that of epoxy-based tests (av. 78 kN) as shown in Fig. 8 and listed in Table 2. The introduction of cement-based filler also notably improves the ultimate load of no-filler tests (av. 46 kN). This suggests that cement-based tests are able to achieve comparable performance to that of epoxy-based tests and are capable of bridging the gap between no-filler and epoxy-based-filler applications. The performance of cement-based filler is much more promising for those two-groove applications as shown in Fig. 12. In this comparison, epoxy-filler tests (No. 22-24) deliver a slightly less average load at the ultimate (95 kN) than that of cement-based tests (100 kN for No. 16-18). This suggests that the strength improvement due to epoxy filler can be compromised by using multiple grooves. Then, cost-effective and environmental-insensitive cement fillers are able to deliver comparable performance to that of epoxy-based equivalence. No-filler tests have the least convergent loads at the ultimate with an average of 78 kN. Cement-based filler is therefore recommended for two-groove applications with a great potential to achieve more stable and larger loads at the ultimate. The filler-related improvement has also been observed for those side-groove applications as shown in Fig. 13. Epoxy-based filler (No. 28-30) is expected to have the best resistance for the vertical slip and therefore achieve the largest ultimate loads (av.= 63 kN). No-filler tests (No. 31-33) failing to resist the vertical slip have the least load (av.= 25 kN). The introduction of high-viscosity cement-based filler is not only facilitate the installation but also provides good resistance for the vertical slip, improving the loads (av.= 43 kN). Compared with the conventional NSM method (see Fig. 14), side-groove applications with high-viscosity cement-based filler might have slight strength loss but they are much more feasible for the retrofitting demands on the bottom of elements. With additional support mechanism, cement-based fillers can be applied for the bottom of one/two-groove applications with a great potential to achieve larger ultimate load than that of conventional NSM method as shown in Fig. 14. By using multiple grooves, the proposed NSM method with cement-based filler can deliver comparable capacity to that of epoxy-based equivalence. Then, the cost-effective, high-viscosity and less environmental-sensitive merits make cement-based fillers to be an excellent replacement for epoxy-based filler in the anchored NSM method. This replacement also suggest a great saving on material cost, an easier-installation and a great potential to have less environmental impacts.

4. Conclusions

This paper aims to deliver a strong NSM method with cheaper, potentially more durable and greater feasibility cement-based filler. Feasible and adequate anchorages were used to make fuller usage of FRP reinforcement for this method. Comparisons between the proposed NSM method and comparable NSM methods have been made to draw the following conclusions.

1. The application of cheaper and potentially more durable cement-based filler helps to deliver more economic and serviceable NSM methods. The high-viscosity filler with a mixing ratio of 1 cement: 3 sand: 0.6 water can be readily used for possible applications on the bottom and side of concrete elements, where conventional epoxy-based NSM methods are generally less feasible.
2. Cement-based filler combined with anchorages were able to fully develop the tensile strength of FRP reinforcement for the one-groove applications. Comparably, the conventional NSM method prematurely failed in concrete rupture which greatly compromised the efficiency of FRP reinforcement for strengthening. Epoxy-based filler tended to better transferring tensile force and therefore helped to achieve stiffer load-deflection responses and larger ultimate load for those anchored NSM tests.
3. By evenly distributing the FRP material of one-groove application into two grooves, anchored NSM tests with cement-based filler were able to achieve comparable load-deflection stiffness to that of anchored NSM tests with epoxy-based filler. This suggests that the performance of anchored NSM methods with cement-based filler can be further improved by distributing the same amount of FRP

material into multiple grooves.

4. Excavating side grooves and then embedding side FRP reinforcement with cement-based filler suggest a much easier application in field. However, side-groove applications suffered from vertical slip, limiting the tensile strength of FRP reinforcement to be effectively developed. In the future, the undesirable vertical slip could be inhabited by a deliberate design of groove geometries or applying multiple anchorages. Then, engineers might have one more option to deliver a stronger, easier, cheaper and potentially more durable NSM method.
5. Cement-based fillers well bridge the gap between no-filler and epoxy-based-filler applications for one-groove, two-groove and side-groove method. With careful design and installation, cement-based tests can achieve comparable loading behavior to that of epoxy-based tests and notably improve the capacity of no-filler applications. Moreover, cement-based fillers are much cheaper, easier-installation, less sensitive to environmental impacts, and doable for bottom application. Cement-based fillers are therefore considered as a promising replacement for epoxy-based fillers.

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Data availability statement

The raw/processed data required to reproduce these findings cannot be shared at this time as the data also forms part of an ongoing study.

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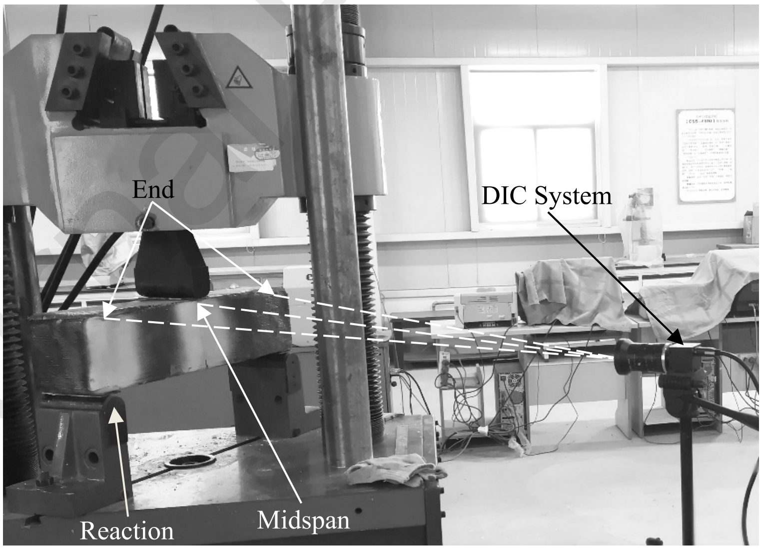
Author Statement

This work entitled **“A novel strong and durable near-surface mounted (NSM) FRP method with cost-effective fillers”** has been done by **Wei Sun, Tiejiong Lou, Mithila Achintha**.

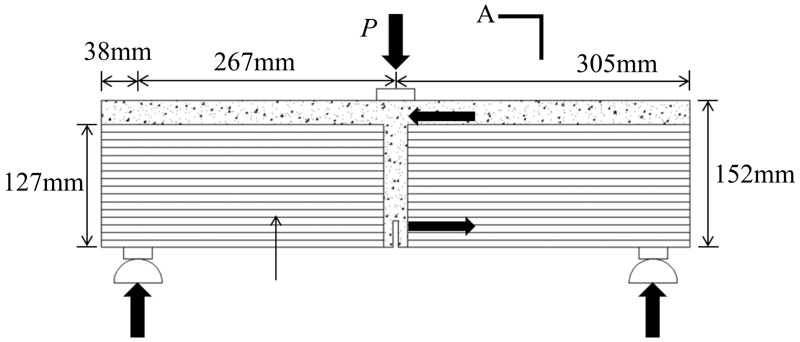
Wei Sun: Investigation, Methodology, Funding acquisition, Experiments, and Writing.

Tiejiong Lou: Experiments, Funding acquisition, and Conceptualization.

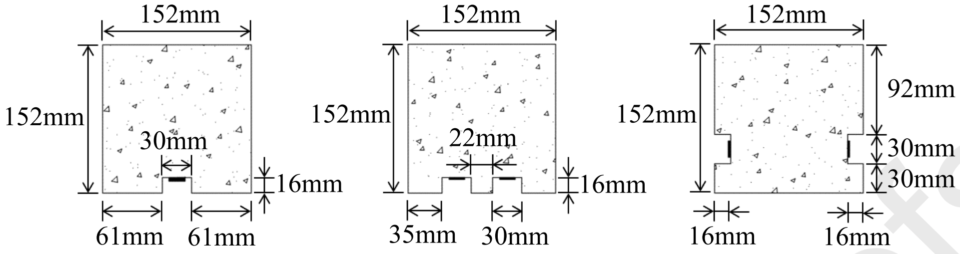
Mithila Achintha: Investigation, Reviewing, and Editing.



(a) Test setup

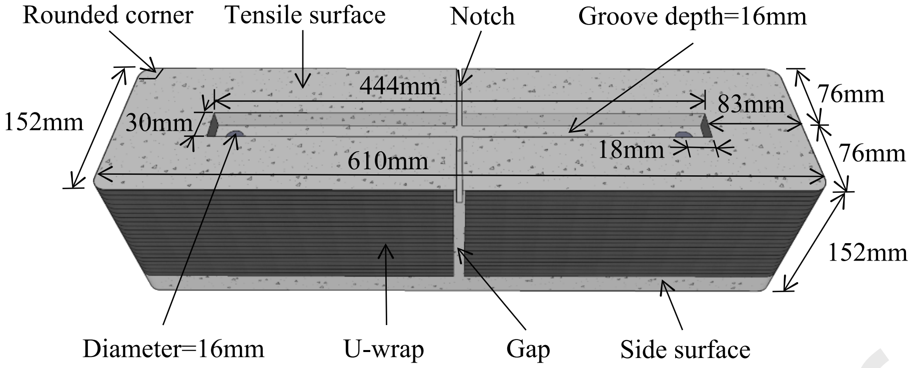


(b) 3-point flexural test

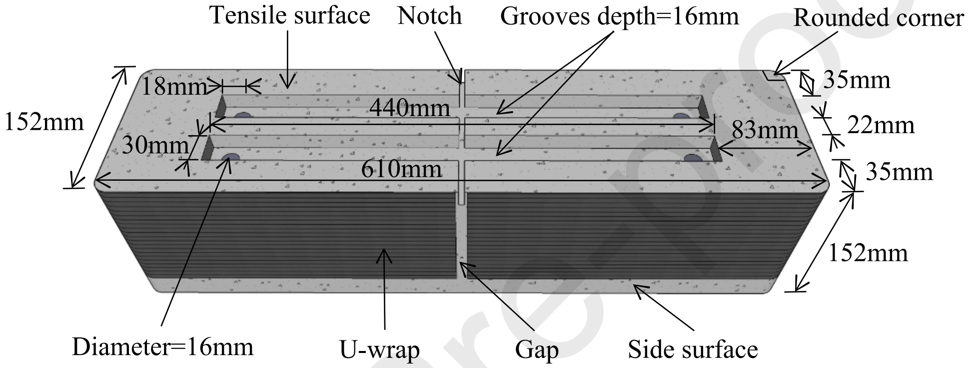


(c) Cross section for one-groove, two-groove and side-groove applications

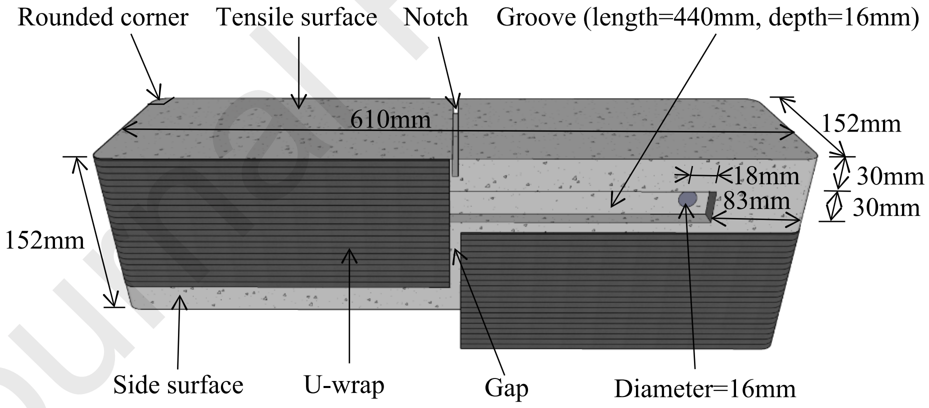
Fig. 1. Test methodology.



(a). Single groove

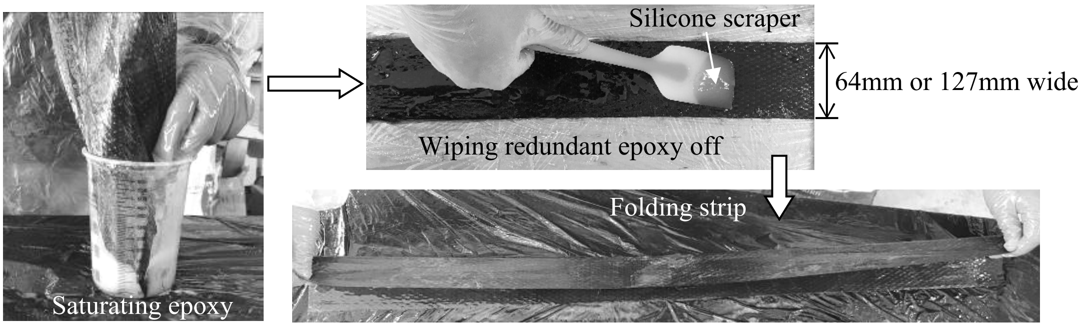


(b). Double grooves

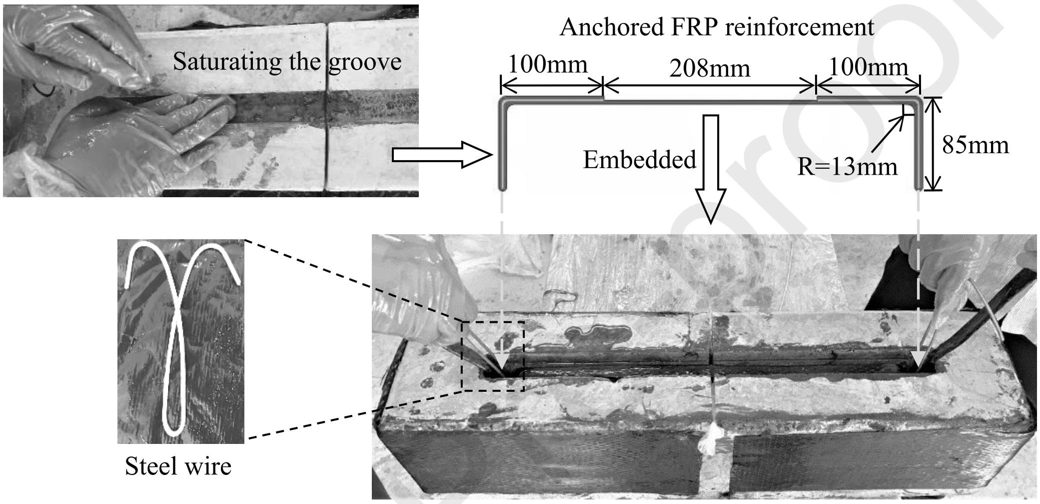


(c). Side grooves

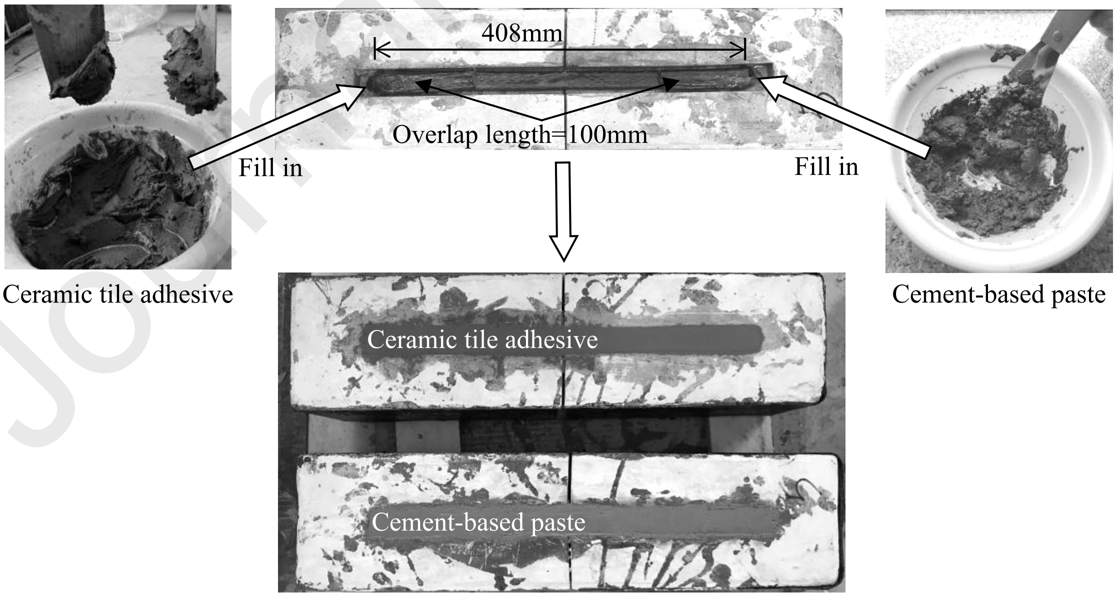
Fig. 2. Experimental specimens.



(a). Fabrication of FRP reinforcements



(b). Installation of FRP reinforcements



(c). Completed specimen

Fig. 3. Fabrication and installation of FRP reinforcements.

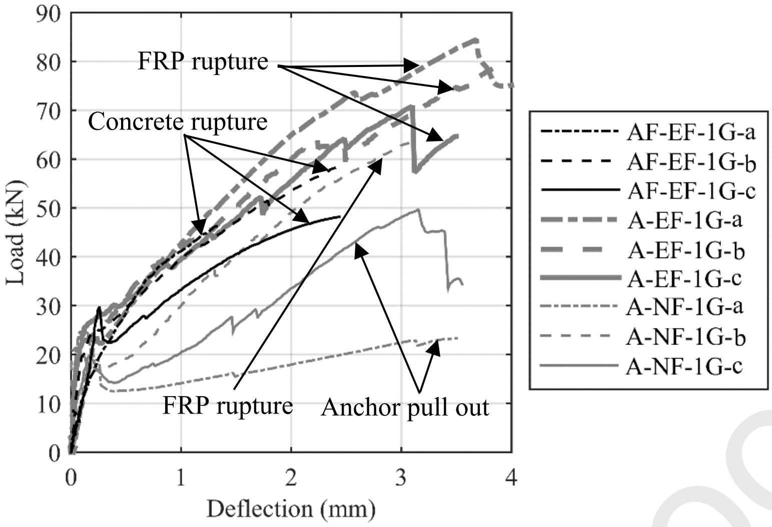
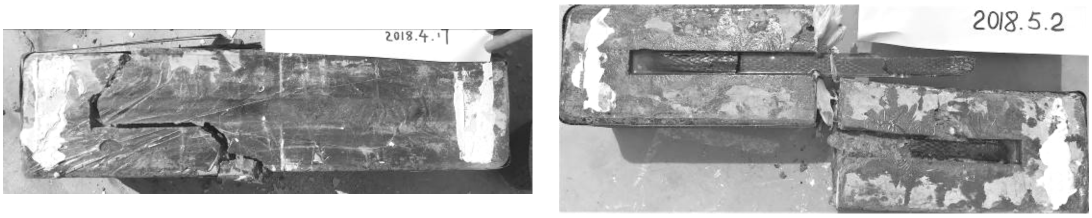
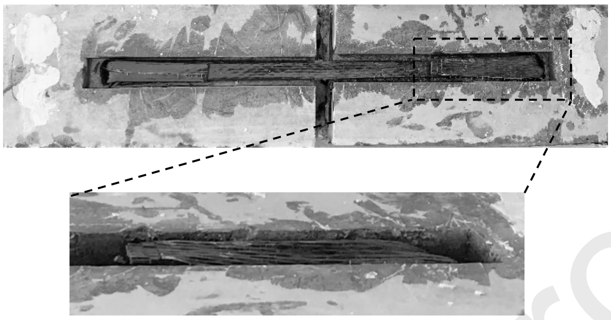


Fig. 4. Load-deflection comparisons of NSM tests with epoxy-based filler or no filler.



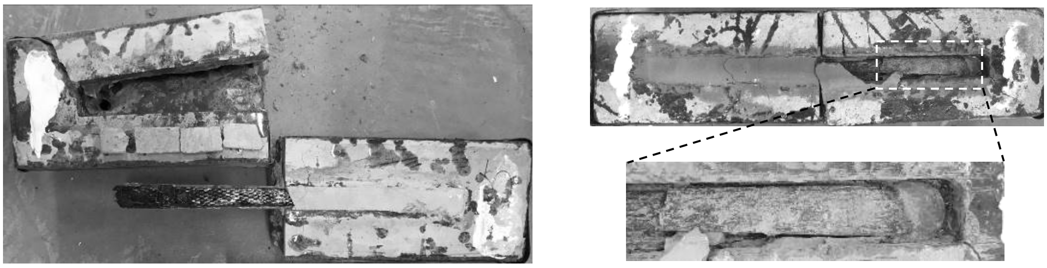
(a). Concrete rupture

(b). FRP rupture



(c). Anchor pull out

Fig. 5. Failure modes of NSM tests with epoxy-based filler or no filler [30].



(a). FRP rupture

(b). Anchor pull out

Fig. 6. Typical failure modes of NSM tests with (a) cement-based filler or (b) ceramic tile adhesive.

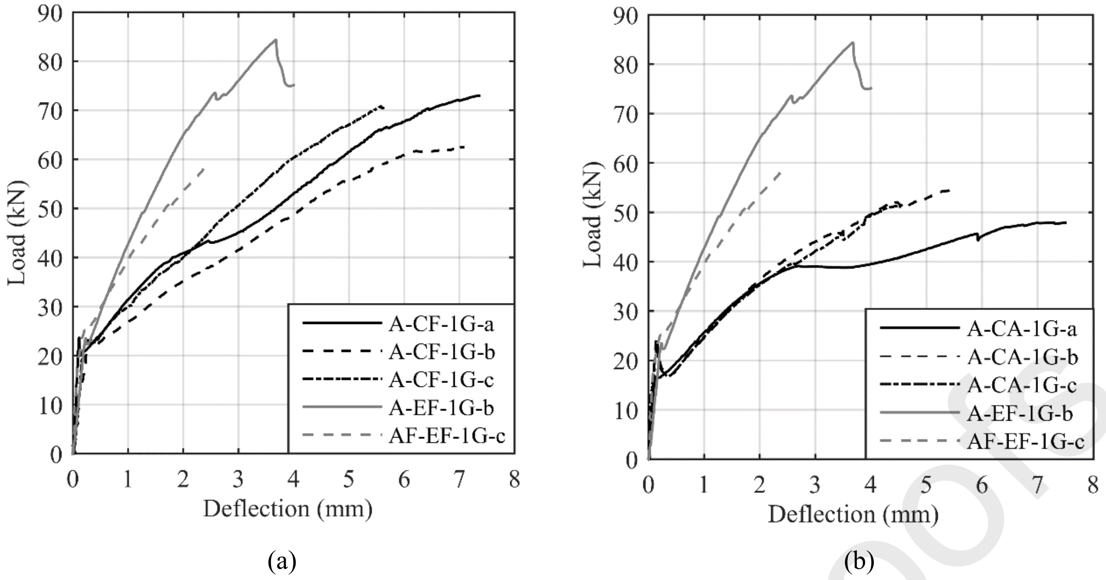


Fig. 7. Load-deflection comparison between typical epoxy-based tests and corresponding tests with (a) cement-based filler or (b) ceramic tile adhesive.

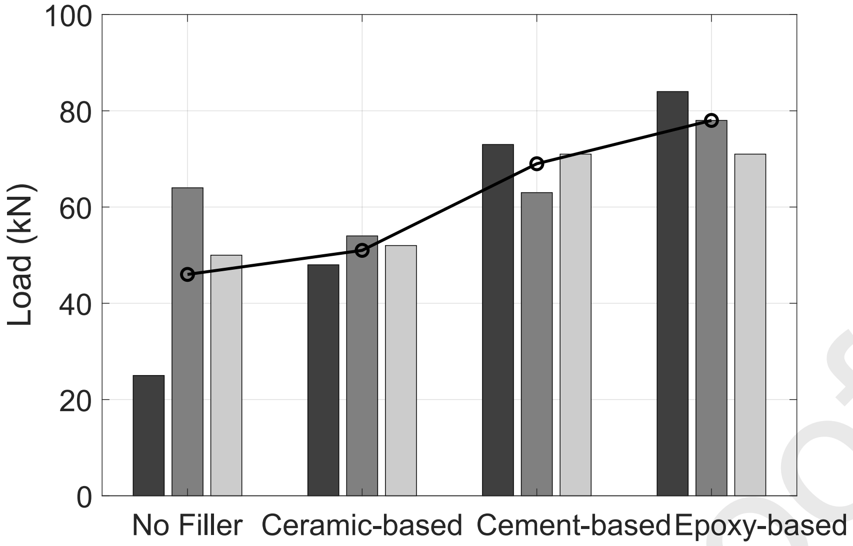
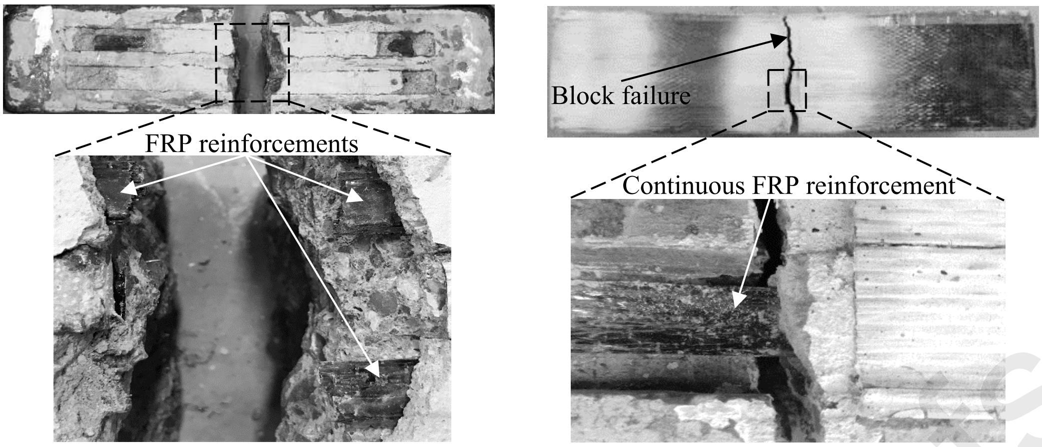


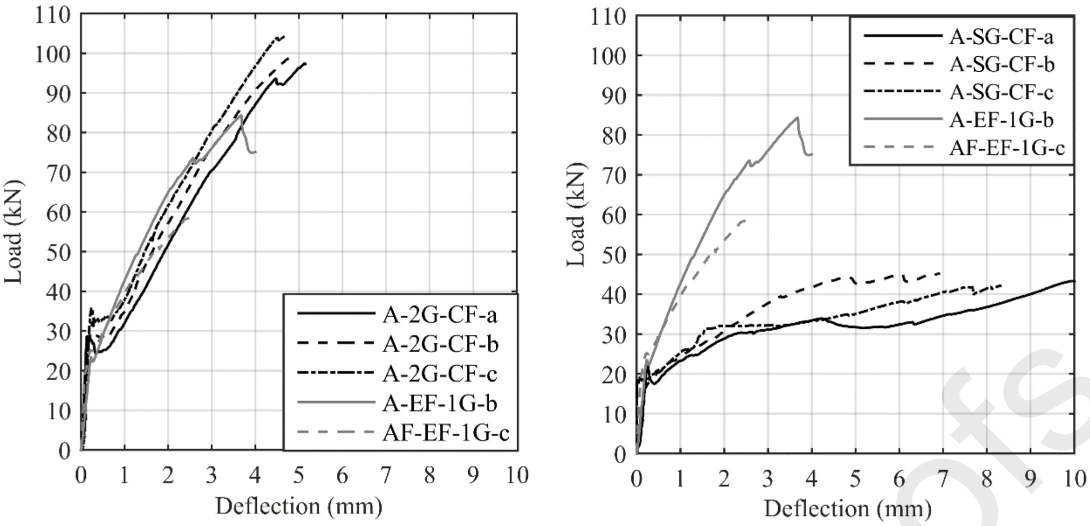
Fig. 8. Ultimate loads of comparable tests with anchorage and various fillers.



(a) FRP rupture

(b) Block failure

Fig. 9. Typical failure modes of (a) double-groove tests and (b) side-groove tests.



(a) (b)

Fig. 10. Load-deflection comparison of typical cement-based tests with (a) double-groove applications and (b) side-groove applications.

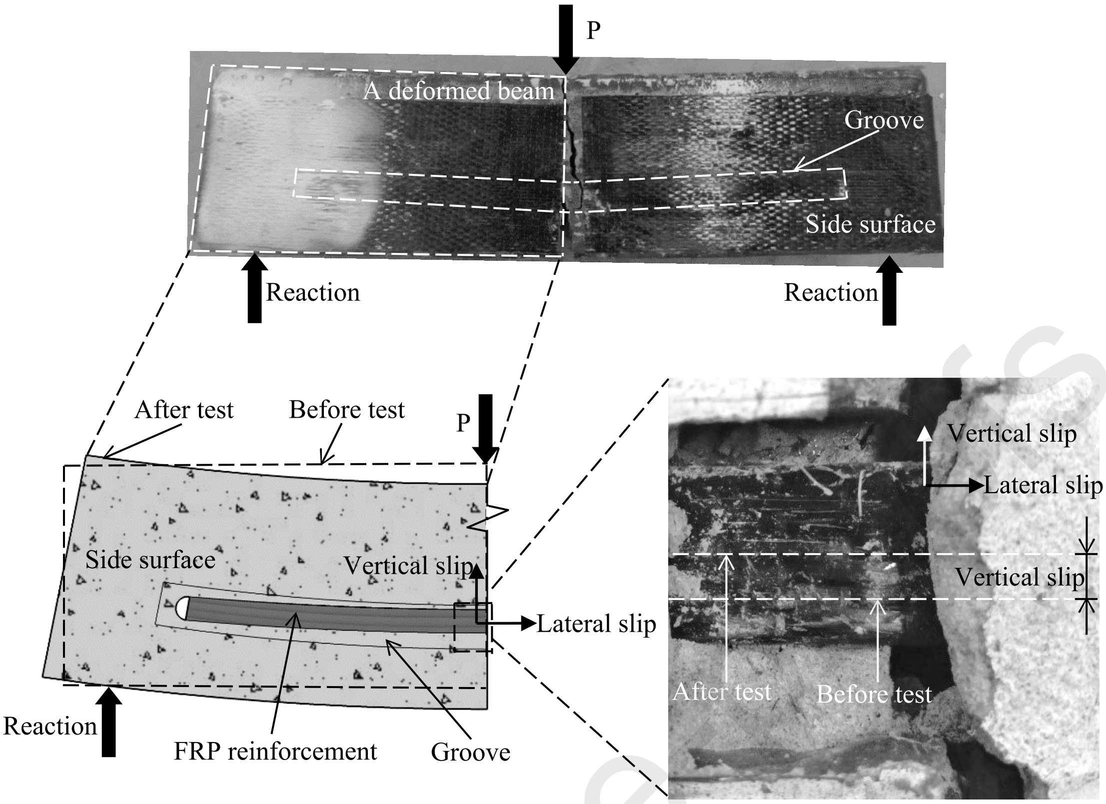


Fig. 11. Slips in a bending specimen with side grooves.

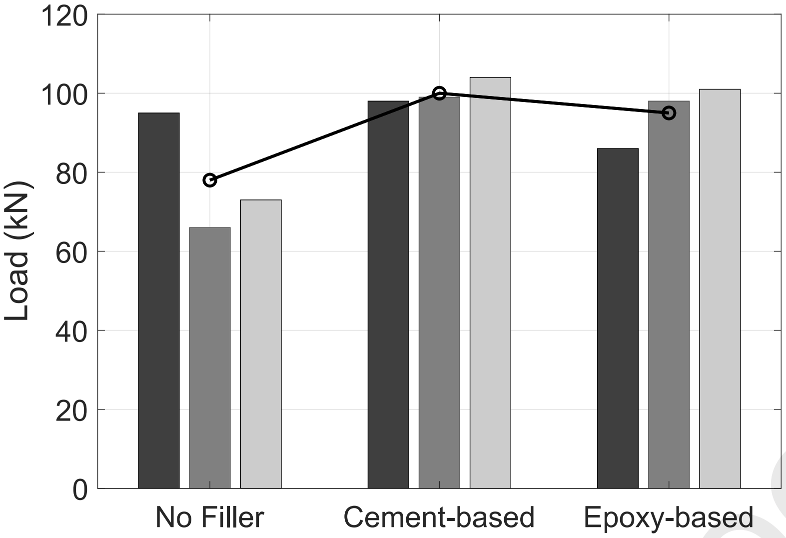


Fig. 12. Ultimate loads of comparable two-groove tests with various fillers.

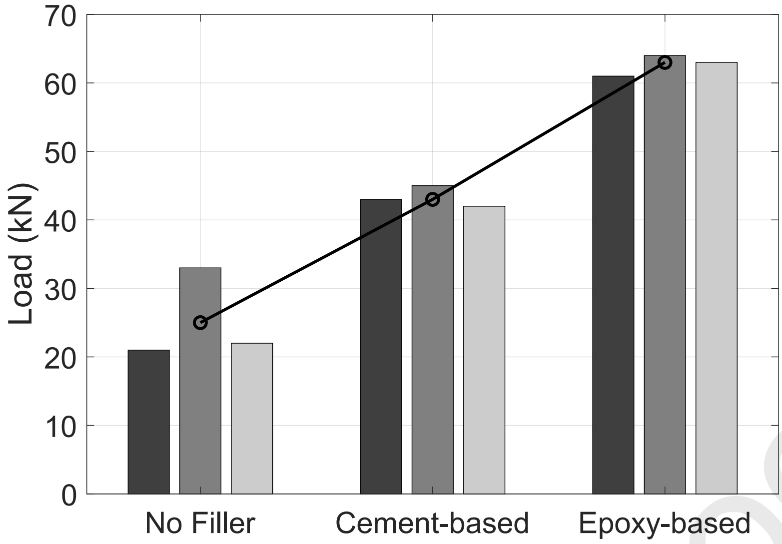


Fig. 13. Ultimate loads of comparable side-groove tests with various fillers.

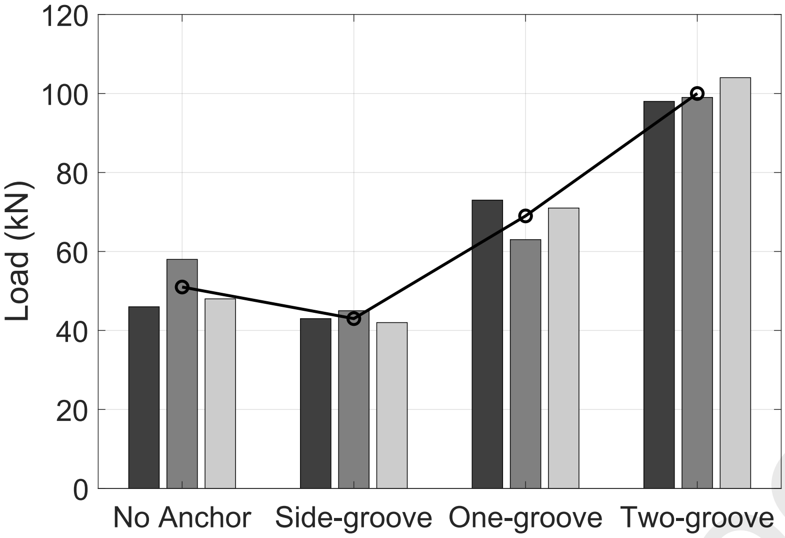


Fig. 14. Ultimate loads of comparable NSM tests, i.e. conventional ones without anchorage, anchored applications for cement-based filler in side grooves, one groove and two grooves.