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Static, fatigue and creep performance of blind-bolted connectors in shear experiments on steel-FRP joints

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ABSTRACT

As traffic loads are ever increasing and bridge infrastructure is ageing, existing materials and connection methods used in renovation and new construction projects are reaching their limits. New materials, such as Fibre-Reinforced Polymer (FRP) in the form of hollow decks can be a competitive solution due to good resistance to fatigue and corrosion. By combining the stiffness provided by steel main and secondary girders with lightweight FRP decks, the properties of both materials can be efficiently utilised. However, the main restriction to the implementation of hybrid steel-FRP structures lies in a lack of knowledge regarding the level of interaction as well as efficient and durable connection solutions of FRP decks and steel girders. Adhesively bonded and grouted connections have been identified as possible connection systems, whereas limited research has been performed on bolted connections. This paper focuses on blind-bolted shear connectors. Connector performance is evaluated experimentally by means of short-term (static) experiments to determine shear resistance and long-term experiments with sustained (creep) and cyclic (fatigue) loading. A vacuum infused GFRP multi-directional laminated plate, 20 mm thick, is connected to steel plates by means of M20 blind-bolts. Static resistance, fatigue and creep behaviour of blind-bolted connectors, as a bearing type, are compared to results of a parallel experimental campaign conducted on slip-resistant injected connectors. A comparable static resistance and ductility is found. However, fatigue endurance is much lower compared to slip-resistant connectors. Therefore, due to low fatigue endurance, low initial stiffness and initial slip, the use of blind-bolted connectors is limited to applications where hybrid interaction and fatigue endurance is not required.

1. Introduction

Hybrid steel-FRP structures represent a competitive option for the renovation of bridges, where the original deck structure made of steel, concrete or timber is deteriorated or underperforming under design loads, whilst the capacity of the main steel load carrying members is still sufficient. Due to its high strength-to-weight ratio, application of FRP decks can impose minimum additional weight on the existing structure. Due to its low weight, prefabrication and installation of large deck segments is possible. This can result in minimum traffic hindrance which is of considerable benefit in bridge infrastructure renovation projects.

The success of designing competitive hybrid steel-FRP repair solutions, as well as new built structures, greatly depends on the structural performance of the deck-to-girder connection. In the case that hybrid interaction between the FRP deck and the girder is to be engaged in a bridge application, a slip-resistant connection is required to obtain a reliable shear interaction and sufficient fatigue endurance. Research on injected, slip-resistant, bolted shear connectors [1] shows that promising solutions are under development which can in future deliver satisfactory fatigue performance for hybrid steel-FRP bridge applications. The focus of the study presented in this paper is to investigate the performance of blind-bolted (not slip-resistant) shear connectors for use in non-hybrid and non- or low cycle fatigue design situations. Exemplary applications are pedestrian, cyclist and light traffic fixed or movable bridges. To this aim, Fig. 1 depicts blind-bolted connections between an FRP deck panel with integrated webs and a steel girder. Lindapter blind-bolts (a.k.a. “hollo-bolts”) were used in this study as they are readily available. Lindapter blind-bolts are originally developed for connections between steel structural components but have been used in various projects where FRP is connected to steel structural components. The

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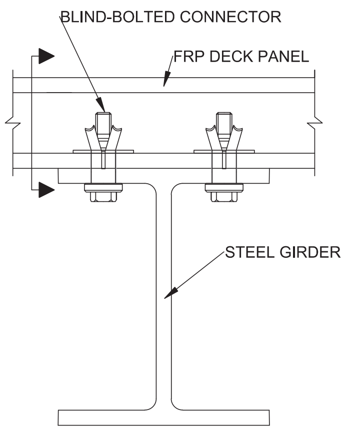

Fig. 1. Example of blind-bolted connection between FRP deck panel and steel girder.

renovation project [2] of a road bridge in Malmo is an example hereof.

A knowledge gap related to bolted steel-FRP connections exists. As opposed to bolted connections, adhesively bonded [3] and grouted shear stud connection [4] between steel beams and FRP decks have been extensively investigated. Bolted connections have rarely been examined due to the localised load transfer, slip behaviour and limited applicability due to difficulties related to the need for bolt installation from both sides of the deck. Blind-bolts, on the other hand, offer possibility for installation from the bottom side of the deck only, leaving the top surface of the deck intact. A summary of relevant publications concerning short- and long-term behaviour of bolted joints in FRP plates in civil engineering is given below.

A type of blind-bolted connection between steel and (pultruded) FRP box profiles has been investigated by [5]. Steel-FRP joints were mechanically fastened by means of M10 blind-bolted connections with locking anchors and loaded under monotonic static tensile loading. Two FRP fibre orientations were investigated, namely bidirectional (connected by a single bolt row) or unidirectional (connected by both single and double bolt rows). The unidirectional FRP fibre configuration demonstrated shear-out under ultimate loading whereas the bidirectional FRP configuration failed simultaneously due to shear-out and net-tension failure. Furthermore, a negligible difference in connector slip modulus (secant stiffness at half the ultimate load) was found between unidirectional specimens with single or double bolt rows.

Bolts with nominal 1 mm hole clearance and blind-bolted connections were tested by [6] in pultruded 5.5 mm thick GFRP panels (polyester resin, E-glass) in double-lap joint configurations. In the study, three stress levels were applied (corresponding to 30%, 50% and 80% the static resistance of the joint) at a stress ratio of $R = 0.1$. A shear-out failure mode was observed for all specimens with both ordinary and blind-bolted joints in both static and fatigue loading. It was found that the static capacity of the joint with blind bolts is 21% less than ordinary bolts, while the fatigue performance is less affected. Note that both connector types are not slip-resistant.

Van Wingerde et al. [7] examined the fatigue resistance of a bolted double-lap joint connecting the webs of pultrude I-profiles (Fiberline). The performance of injected bolts was compared to that of ordinary bolts. Pin-bearing was the dominant failure mode in all specimens. The authors reported an S-N curve exponent of −11.7 and −5 for ordinary bolts at load ratios of $R = 0.1$ and $R = -1$, respectively. In contrast, S-N exponents of −11.7 and −9 were reported in the case of injected bolts, thereby substantiating the 100 times improved fatigue behaviour of injected bolts over bolts with hole clearance when exposed to fully reversed cyclic loading.

This paper presents the findings of an experimental investigation into the creep and fatigue performance of Lindapter blind-bolted connectors. The static resistance of 20 mm diameter connectors is determined in single-lap shear joint configuration between FRP and steel plates of 20 mm thickness. The same set-up is used to obtain creep deformation under 2 months sustained loading (25% of the ultimate load). Preliminary recommendations for fatigue limits are provided based on cyclic experiments at three load levels. The static, fatigue and creep performance of blind-bolted connectors is compared to the performance of slip-resistant connectors tested in the same experimental set-up as presented in [1].

2. Experimental set-up

Static resistance was determined by applying monotonic static tensile shear loading (Series S2) in single-lap joint configuration. Series F2 refer to specimens that were subjected to cyclic loading, and C2 to a combined sustained (creep) and cyclic (fatigue) loading. The long-term sustained (creep) loading was applied as approximately 25% of the ultimate shear resistance. The naming convention is: F = cyclic (fatigue) loading; C = sustained (creep) loading + fatigue (cyclic) loading. A sustained (creep) loading of 40 kN in shear was applied for 2 months. Referral to individual specimens within an experimental series is indicated by a specimen number (i.e. C2-1 is specimen 1 of series C2). Individual specimens, in turn, consist of two connectors labelled top (T) and bottom (B) owing to specimens' vertical orientation during testing. For some analysed behaviour this enabled doubling of the number of individual results for a single test, such as: initial stiffness, slip load, creep deformation.

Research on blind-bolted connectors was performed simultaneously to that on slip-resistant connectors [1]. The series number 2 (e.g. S2, C2 or F2) refers to blind-bolted connectors presented here. iSRR and Injected Bolt (IB) connectors [1], denoted as series 1 and 3, respectively, will be referred to in the discussion section of this paper for comparative purposes. Table 1 presents an overview of experiments performed on blind-bolted connectors – Series 2.

2.1. Specimens and materials

As seen in Fig. 1, the connectors in a real bridge deck application are located inside the FRP deck panel. In this experimental investigation, specimens were prepared in single-lap shear joint (SLJ) configurations, as depicted in Fig. 2, resembling the connection of the steel plate and the bottom facing of the FRP deck panel. As such, the webs and top facing of the FRP deck are excluded in the performed experiments, as well as the foam core. Such a set-up facilitates the observation of connection failure mechanism. Lower bound estimate of mechanical performance in an FRP panel is obtained in SLJ set-up, because one FRP plate suffers a larger influence of bending due to eccentricity compared to the whole panel comprising two FRP plates connected by core webs. In all specimens, a single FRP plate (160 mm × 400 mm × 20 mm, w × l × t) is connected to two S355 steel plates (110 mm × 330 mm × 20 mm) by means of M20 grade 8.8 Lindapter blind-bolts (product code HB20-2 [8] shank diameter of 20 mm and nominal sleeve outer diameter of 33 mm) at both ends. The measured diameter of the sleave is 32.75 mm. All connectors were installed with a 220 Nm torque. This torque level is below the level specified by the producer for use in steel to steel connections, namely 300 N·m for M20 Lindapter blind-bolted connector. This lower level of torque was obtained in installation try-outs to be high

Table 1
Applied loading regimes and number of specimens of blind-bolted connectors (each specimen consists of 2 connectors).

Experimental Series	Static Loading	Sustained Loading	Cyclic Loading
S2	3		
F2			5
C2		3	2*

* After sustained loading.

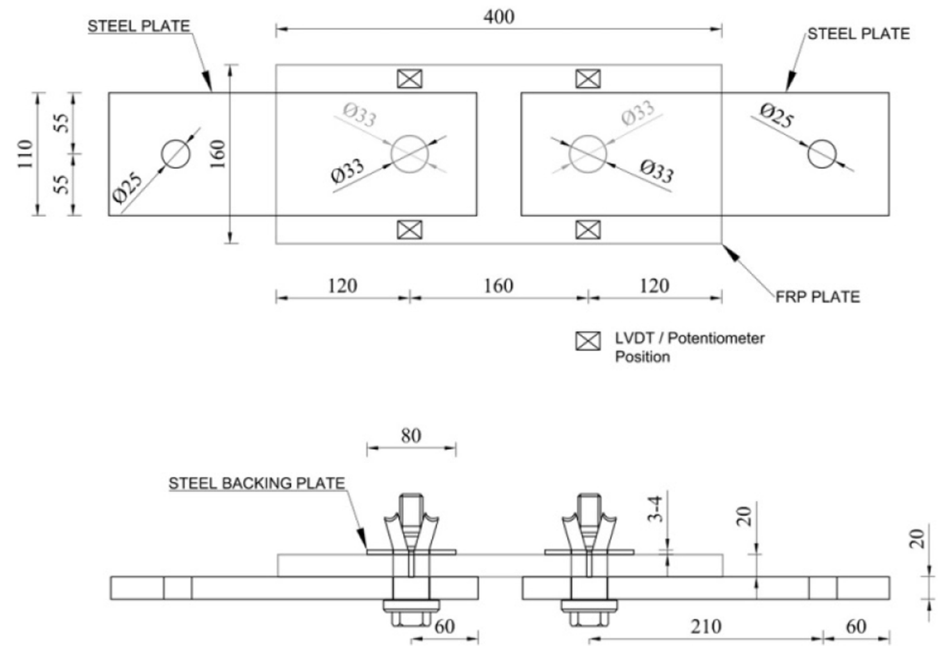

Fig. 2. Blind-bolted connectors in steel-FRP single-lap shear joint specimens (dimensions in mm).

enough to ensure opening of the expandable sleeve but not too high to result in crushing of the FRP laminate.

In order to spread the preloading by the sleeve and improve through-thickness loading on the laminate, a steel backing plate was applied, as shown in Fig. 2.

The vacuum-infused GFRP plates were fabricated with unidirectional and non-woven bi-directional fabrics of E-glass fibres (600–1200 g/m^2) and a DCPD-polyester resin. The stacking sequence is as follows: $[90/0;0_3; \pm45_2; 0/90; 0_2; \pm45; 0/90; 0]_s$. Lay-up and stacking sequence of the laminate results in a composition of: 0°/62.5%; 90°/12.5%; +45°/12.5%; −45°/12.5%. This lay-up was selected to adhere to the requirement of at least 12.5% of fibres in each of the main material directions (0°, 90°, +45°, −45°) as specified in the design recommendation CUR96 [9]. The design fibre volume fraction is 54%. In the intended application in hybrid steel-FRP bridge structures, the orthotropic FRP deck panel is assumed to span between the main or cross girders. This means that the main interface shear forces acting on the connectors due to hybrid interaction between the FRP deck and steel girders will be perpendicular to the principal direction of fibres in the laminated plates of the FRP deck panel. Properties of the multi-directional laminate in the direction of loading are determined according to relevant ISO and ASTM standards with at least 5 specimens with acceptable failure mode per test series. The obtained average values and variation are presented in Table 2.

2.2. Loading and measurements

All the experiments on connector specimens were performed in a hydraulic testing rig, with a capacity of 600 kN, where steel plates are fully clamped in hydraulic jaws. The static resistance is determined by applying a monotonic tensile load resulting in a shear load in the connectors. The load was applied in a quasi-static manner by a controlled displacement rate of 0,01 mm/s. The load level of 40 kN shear in connectors applied in the long-term loading experiments was selected as approximately 25% of the shear resistance, same as for slip-resistance connectors, see details in [1].

Table 2
Mechanical properties of the FRP laminate in transverse direction (direction of loading).

Mechanical property	Average value and (CoV)
Transverse compressive strength - $f_{y,c}$	172 MPa (5.3%)
Transverse compressive modulus - $E_{y,c}$	19.1 GPa (6.6%)
Transverse tensile strength - $f_{y,t}$	173.7 MPa (5.2%)
Transverse tensile modulus - $E_{y,t}$	7.7 GPa (2.9%)
transverse bearing strength - $f_{y,br}$ *	334 MPa (2.4%)

* Tested in accordance to ASTM D953 Procedure C [10].

Independent connector slip behaviour of the 2 connectors in one specimen was determined by placing pair of linear variable differential transducers (LVDTs) on both sides of each connector. The same configuration of 4 LVDTs was used in the cyclic load experiments (series F2), as shown in Fig. 3.a. In the cyclic loading experiments, a load ratio of R = −1 was selected to investigate the loading situation where the highest degradation rate is expected according to current literature [7]. Three cyclic load levels were applied to different specimens, namely ±20 kN; ±30 kN and ±40 kN.

In the long-term sustained loading experiments (Series C2), a set of 4 potentiometers per specimen (installed in a comparable manner as the aforementioned LVDTs) were used to monitor the displacement increase. Specimens were connected in series and hung vertically in two strings within a testing rig a shown in Fig. 3.b. The desired load level was maintained by means of springs at the top of the tower and re-tensioning during the experiment.

3. Results

3.1. Shear resistance – static experiments

Individual connector force-displacement curves were obtained by averaging the LVDT measurements of slip displacement between the FRP and steel plate at both sides of a specific connector. The connector force-displacement curves are plotted in black and grey in Fig. 4.a. The individual connectors were monitored until a connector level displacement of approximately 10 mm was reached, equal to the limit capacity of the LVDTs. Beyond 10 mm displacement, further load-displacement behaviour is available as an average result of 2 connectors per specimen, obtained by calibrating the hydraulic jack stroke displacement, as shown in Fig. 4.b.

Slip occurred at a low load level (<10 kN) as seen in Fig. 4.a. This is

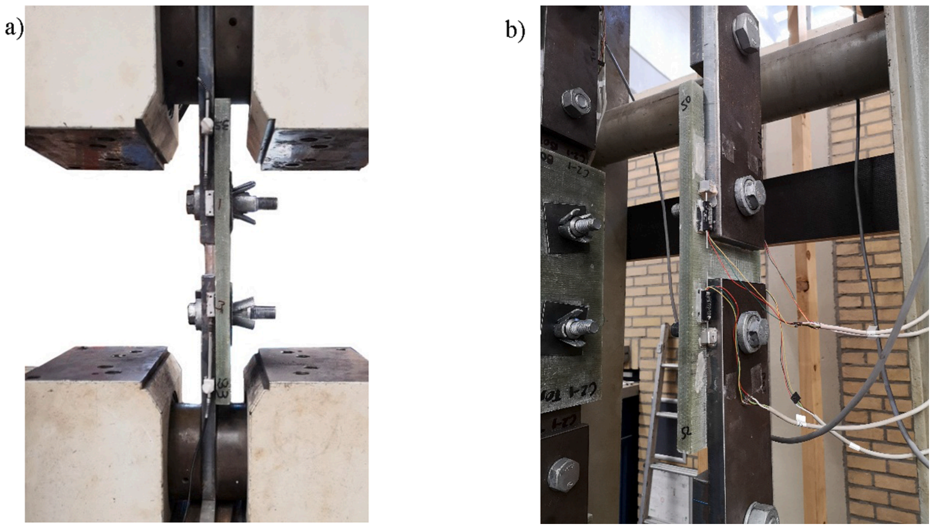

Fig. 3. Test set-up: a) static and cyclic loading experiments and b) sustained loading experiments.

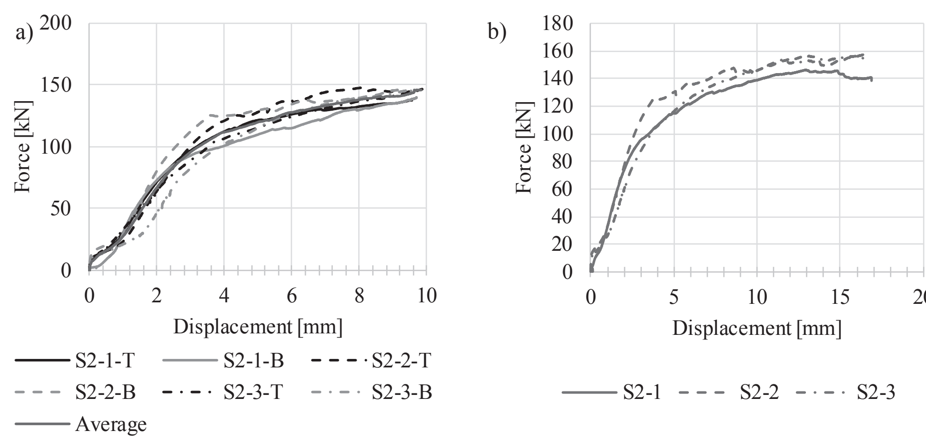

Fig. 4. Connector shear resistance. a) as recorded per connector by LVDTs, b) connector displacement until failure (scaled specimen displacement).

in accordance with the findings of [5] regarding the behaviour of blind-bolted connectors used in single lap joint configurations between steel and FRP. After this initial slip of approximately 1 mm, load transfer is continued once bearing load transfer is engaged by the blind-bolted connector coming into direct contact with the hole in the FRP and steel plate. The shear connector stiffness is determined as the slope of the linear part of the load-displacement curves, referred to as k, and listed in Table 3. An average value of 45.0 kN/mm with CoV = 22.9% is obtained. In addition to the aforementioned parameters, shear connector stiffness was also determined in accordance with EN1994-1-1 [11], calculated as the secant stiffness at 70% of the ultimate resistance. The resulting averaged connector stiffness (k_{sc}) is 29.2 kN/mm (CoV 18.4%).

The connector shear resistance is determined as the load level at which it was no longer possible to increase force by increasing displacement, see Fig. 4.b. The average value of the shear resistance is 153.8 kN, with CoV = 4.4%. Specimens show significant ductility, as bearing failure is governing, with an associated shear displacement of at least 15 mm in all experiments. No significant signs of net-section failure of the FRP plates was observed, as the layup and width of the specimens were designed not to have this failure mode. To demonstrate the substantial degree of bearing failure and connector deformation, Fig. 5 depicts the state of the specimen in a late stage of loading, at approx. 12 mm of connector shear deformation. It can be seen that significant bearing damage of the FRP plate as well as rotation and plastic deformation of the blind-bolted connectors occurred.

Table 3
Shear connector stiffness.

	S2-1-T	S2-1-B	S2-2-T	S2-2-B	S2-3-T	S2-3-B
k [kN/mm]	44.5	61.3	39.4	52.0	32.2	40.6
k_{sc} [kN/mm]	30.9	24.6	32.6	37.6	25.8	24.1

3.2. Sustained loading - creep experiments

During the two months of sustained 40 kN tensile shear load in a single lap set-up, individual connector displacement was monitored. The initial displacement δ_e resulting from the load application at the start of the experiment was recorded and subtracted from the total measured displacements δ. As such, the creep displacement δ_c resulting from sustained loading only are determined. The results per connector as measured on 3 specimens (each consisting of two connectors labelled top T and bottom B), are shown in Fig. 6.a.

In addition to monitoring the displacement increase under sustained loading, the creep factor φ(t) per connector was determined according to Eq. (1). The result is shown in Fig. 6.b.

$$\frac{\delta}{\delta_e} = 1 + \varphi(t) => \quad \varphi(t) = \frac{\delta}{\delta_e} - 1 \tag{1}$$

After 2 months of sustained loading the creep displacement was 0.15

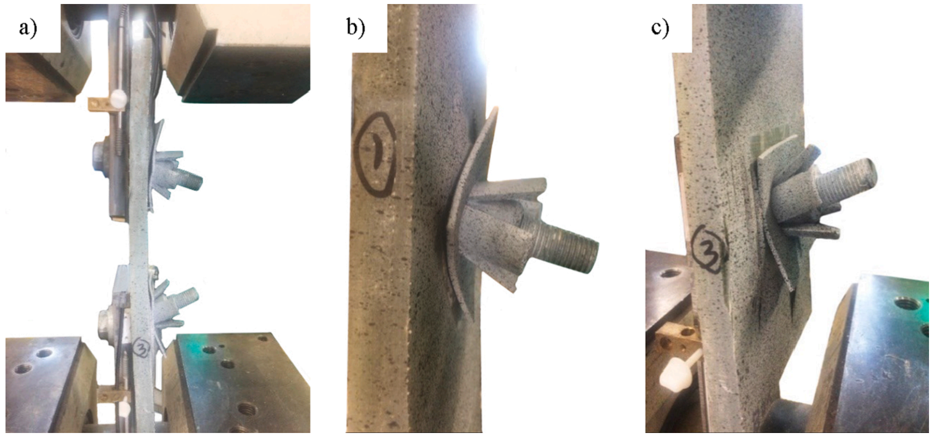

Fig. 5. Ultimate failure under static loading. a) entire specimen, b) S2-2-T connector, c) S2-2-B connector.

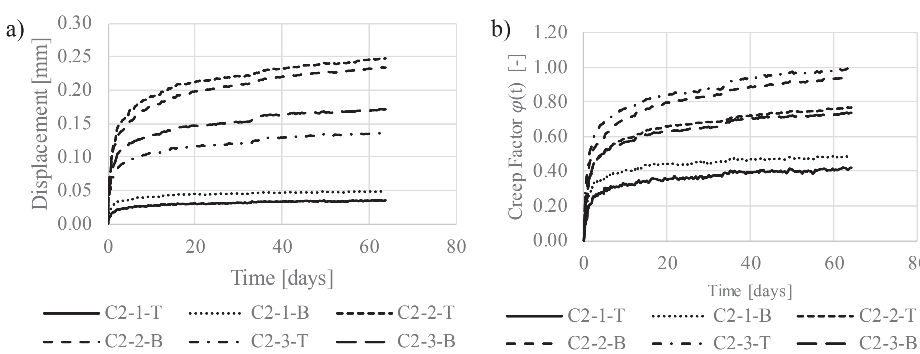

Fig. 6. Creep behaviour. a) displacement and b) creep factor.

mm on average for 6 connectors. However, huge scattering of the results was found with a coefficient of variation CoV = 62%. The average creep factor was calculated as 0.72 [−] with somewhat smaller variation CoV = 32%.

3.3. Cyclic loading - fatigue experiments

The aim of the experiments shown here is to determine the preliminary F-N curve (connector shear load vs. no. of cycles) for blind-bolted connectors and to compare the fatigue endurance to slip-resistant connectors shown in [1]. As demonstrated in the monotonic static loading experiments, blind-bolted connectors experience slip behaviour at low load levels (<10 kN). As such, it was not sensible to impose the same criterion of 0.3 mm displacement increase as in case of slip-resistant connectors [1]. Instead, blind-bolted specimens were tested under three levels of reversed cyclic load (±20 kN, ±30 kN, ±40 kN) until either FRP bearing failure or blind-bolt connector fracture was recorded. Load levels, instead of levels of bearing stress, are used in presentation of the results for several reasons. First, bearing stress in single-lap shear connection is not deterministic, as it is non-uniform through the depth of the bolt holes due to eccentricity, clearance, etc. Second, determining the connectors' fatigue endurance using force levels allows for a comparison of the results between different connector types. The number of cycles to failure (FRP bearing or bolt fracture) per load level for each specimen is documented in Table 4. In total 7 specimens of blind-bolted connectors were tested with 11 independent results. At the lowest load range of ±20 kN, it was possible to obtain independent results from both connectors of one specimen by clamping the side of specimen where the 1st connector failed and continuing the loading cycles, as described in detail in [1] for injected bolts. Four independent results were obtained from the two cyclically loaded

Table 4
Blind-bolted connectors – average results of fatigue experiments.

	Bolt failure		Bearing failure	
Load level	Average cycles to failure	No. of results	Average cycles to failure	No. of results
±20 kN	283,248		–	–
±30 kN	73,336	2	31,894	2
±40 kN	–	–	8054	3

specimens at the ±30 kN load range by means of identifying mixed-mode failures.

To differentiate between bearing and bolt failure, Fig. 7 displays curves of the connector displacement vs load cycle from the representative specimens at the three tested load levels. Connectors subjected to ±40 kN (red lines) and ±30 kN (black lines) experienced a rapid increase in displacement range after reaching the value of 2 mm due to extensive FRP bearing failure. Subsequently, bearing failure is defined in this study as the rapid increase in bolt displacement as the bolt bears into the laminate, without the occurrence of net section failure in the laminate. In contrast, specimen F2-4 and F2-5 (marked in grey, ±20 kN cyclic loading) showed very limited increase in connector displacement and experienced sudden bolt fracture. From the aforementioned, it is postulated that the threshold of 2 mm increased connector displacement should be imposed on blind-bolted connectors to prevent the occurrence of extensive FRP bearing failure at higher (±30 kN and ±40 kN) load levels, corresponding to low cycle fatigue. It is important to note that this observation is only valid for the investigated single-lap joint specimens of Lindapter M20 blind-bolts with specific dimensions/features: diameter of the hole and sleeve of 33 mm; thickness of 20 mm and type of the FRP plate; presence of the backing plate, see Section 2.1, loaded in

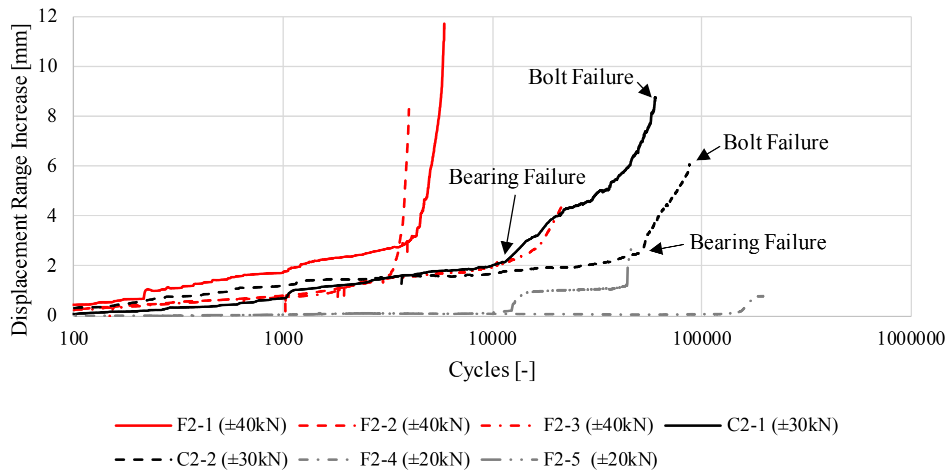

Fig. 7. Connector displacement increase vs number of cycles.

transverse direction. For the same thickness and type of FRP plate and type of connector, the results presented here can serve as conservative estimate of behaviour in FRP deck panel where boundary conditions are favourable compared to single-lap shear test set-up due to less eccentricity in the load transfer. For blind-bolted connectors with other bolt and/or sleeve diameter, thickness or type of FRP plate and direction of load, the performance and failure modes will be different.

A relatively small increase of displacement was obtained in creep experiments 0.25 mm vs. the increase of displacement range of more than 2 mm as result of bearing failure due to cyclic loading, see Fig. 6 vs. Fig. 7. Therefore, the specimens used in creep experiments were reused in the fatigue experiments, for a load range of ±30 kN, to extend the dataset with more loading ranges. This is a conservative assumption used to build preliminary F-N curve as specimens with no prior creep loading would be able to survive more load cycles.

Cyclic loading at the highest load range of ±40 kN resulted in bearing failure of the FRP after 8054 cycles on average from 3 specimens. Connectors in these specimens suffered a huge slip displacement due to bearing failure, followed by bolt loosening. Continuation of load cycles to determine final fracture of the connectors at this load level was not possible. The severe bearing deformation was also followed by substantial delaminations in the FRP plate around the connector, see Fig. 8.a. Bearing failure of the FRP plate is not visible in Fig. 8.a. as it is covered by the steel backing plate. At a load range of ±30 kN, bearing failure of the FRP plate commenced on average after 31.9k load cycles from 2 specimens. The integrity of specimens after the bearing failure was sufficient to continue loading cycles up to final bolt fracture after 73.3k load cycles on average. At a force range of ±20 kN, no significant bearing failure was observed. Fracture of the blind-bolted connector was observed on average after 283k load cycles, based on 4 results. In all specimens tested at ±20 kN and ±30 kN, the bolt fracture occurred at the location beneath the head, see Fig. 8.b.

4. Discussion

Connector performance in case of short- and long-term loading of blind-bolted shear connector is compared to the performance of slip-resistant connectors, iSRR and injected bolts, presented in [1]. The slip-resistant connectors were tested in parallel to blind-bolted connectors in an identical experimental methodology.

4.1. Short-term - static performance

As seen in Fig. 4, all blind-bolted connectors slipped under applied tensile shear loading at a load level below 10 kN. In contrast, slip was not recorded in the injected bolt specimens, whereas slip occurred on average at 56.4 kN in the iSRR connectors [1]. Initial shear stiffness of the blind-bolted connectors is less than 40% as compared to slip-resistant connectors [1]. The shear resistance (average ultimate shear load) of both slip-resistant and blind-bolted connectors are comparable ranging between 143.5 kN and 153.9 kN. The low slip-resistance threshold together with low shear connector initial stiffness excludes application of blind-bolted connector in applications where hybrid interaction between FRP and steel structural members is required. For

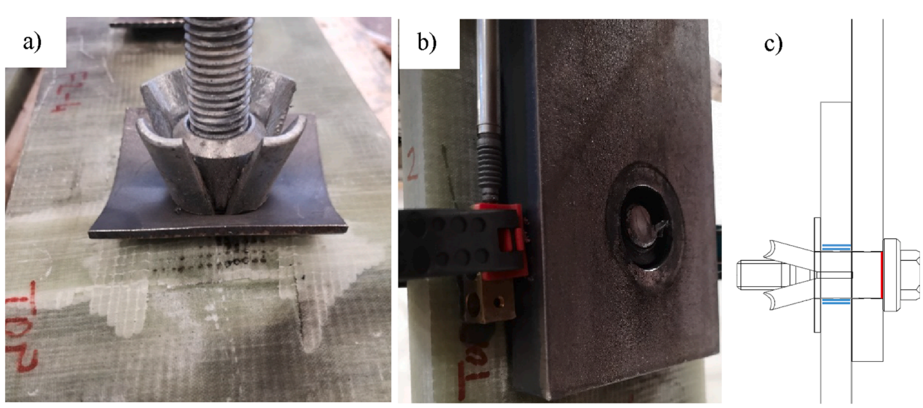

Fig. 8. Failure in cyclic loading experiments: a) bearing failure at ±40 kN; b) bolt fracture at ±20 kN and ±30 kN and c) failure positions (bearing failure position indicated in blue and bolt fracture position in red). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

example, in highway bridges, where the deck connection is exposed to substantial fatigue loads with millions of cycles, the resulting slip in the connection would result in too much wear in the FRP and steel bolt. The resulting low fatigue endurance of the blind-bolted connection would lead to unacceptable maintenance and reliability issues. However, the application of blind-bolted connectors in non-hybrid structures is possible. Blind-bolted connectors have been used to connect FRP to steel structural components in number of design situations where hybrid interaction is not engaged, such as employed in [2].

4.2. Long-term - creep and fatigue performance

Table 5 summarises the additional displacement δ_c due to creep effects over two months under sustained 40 kN tensile shear (25% of ultimate load) in both the blind-bolted and slip-resistant connectors. The blind-bolted connectors show a high degree of scatter of creep deformation as compared to slip-resistant connectors. In comparison to the iSRR connectors, blind-bolted connectors showed a 46% higher averaged creep displacement after two months of loading coupled with x2.4 higher CoV. The larger scatter of creep deformation and creep factor of the blind-bolted connectors is attributed to less restriction against rotation of the connector compared to slip-resistant connections It should be noted that connector performance was assessed by applying the same force level to all connector types without correcting for different bearing stresses due to varying connector diameters. Comparison on bearing stress level would be inconclusive because each connector type has a different load transfer mechanism. If the trends of secondary creep stage are extrapolated, for reasons of comparison, blind-bolted connectors and injected bolts would reach the criterion of additional 0.3 mm connector displacement rather soon - in an order of magnitude of 10 years. The iSRR connectors on the other hand would reach the same criterion in an order of magnitude of 100 years. In neither case, a strong influence of creep on fatigue performance was found.

The fatigue performance of blind-bolted connectors is exceptionally low compared to slip-resistant connectors. On the basis of cyclic loading experiments with the same load level of ±40 kN, blind-bolted connectors withstand on average 8 thousand cycles until excessive bearing failure occurs, whereas iSRR and injected bolt connectors withstand 2.31 million and 23.7 thousand cycles, respectively, with no failure at all [1]. In the latter, the criterion of 0.3 mm additional connector displacement was applied as for slip-resistant connectors. The conclusion of [1] is that slip resistant connectors are suitable for application in highway bridges where hybrid interaction between steel and FRP is required. In contrast, blind-bolted connectors are not recommended for hybrid structural systems where large number of cycles of high shear forces in connectors would be expected. Example are connection forces in hybrid steel-FRP highway bridges, due to traffic and temperature loads.

In non-hybrid bridge applications, substantially lower shear load cycles would be imposed. Although the hybrid interaction is not intended in those cases, the small but existing shear stiffness of the connectors, see Section 3.1, will result in low level shear load cycles in the connectors. Those forces would need to be determined in detailed structural analyses, where stiffness of the connectors is explicitly modelled or to be determined by tests. In order to provide information for investigating the feasibility of blind-bolted connectors in such applications, F-N curves are constructed and shown in Fig. 9. F-N here stands for force range vs. number of cycles to failure. The F-N curve presented here is a preliminary curve for M20 blind-bolted connectors in single-lap shear tests in a 20 mm multi-directional laminated GFRP plate loaded in transverse direction by fully reversed load cycles (R = −1) based on the limited number of tests presented in this study. Values indicated on the vertical logarithmic axis correspond to the maximum forces per connector, e.g. 40 kN, 30 kN and 20 kN in fully reversed shear load cycles of ±40 kN, ±30 kN and ±20 kN, respectively (see Fig. 10).

Table 5
Creep behaviour of blind-bolted vs. slip-resistant connectors after two months at 25% of ultimate load.

	Blind-bolted connectors	Slip-resistant connectors [1]	
	Lindapter	iSRR	Injected bolts
Average additional displacement δ_c [mm]	0.15	0.10	0.17
Displacement CoV [%]	62	25	25
Average creep factor φ(t) [-]	0.72	0.66	0.62
Creep Factor CoV [%]	32	11	21

Averaged F-N curves corresponding to FRP bearing and steel bolt fracture give an indication of the fatigue performance. To give a better impression of the true fatigue behaviour, more specimens would be required. ASTM E739 [12] suggests between 12 and 24 specimens are required to determine fatigue curves with statistical significance.

In addition to averaged F-N curves, a preliminary statistical analysis is performed according to the specifications of ASTM E739 [12], disregarding the existence of different failure modes. The method makes use of a process of linearization in the following form:

$$\mathrm{Log(N)} = \mathrm{A} + \mathrm{B} \cdot \mathrm{Log}(\mathrm{F_{max}}) \tag{2}$$

With $\log(\mathrm{N}) = \mathrm{Y}$ and $\log(F_{max}) = \mathrm{X}$, the following linear F-N relationship is defined:

$$\mathrm{Y} = \mathrm{A} + \mathrm{B} \cdot \mathrm{X} \tag{3}$$

Whereby A and B are the regression parameters defined by means of a linear regression. The 95% confidence bands are constructed around the linear F-N curve by taking into account the variance of all Y points as well as a factor $\mathrm{F_p}$, accounting for the number of specimens and force levels tested. The assumption of linearity assumed previously was also tested and verified according to the method proposed in [12]. The number of cycles corresponding to the 95% (upper and lower) confidence bands are listed in Table 6:

The aforementioned statistical analysis yields B = −4.40 (slope of the F-N curve) and A = 10.99. This slope is found to be steeper than that reported by [7] concerning pin bearing failure of FRP laminates with ordinary M16 bolted connections in a double-lap shear configuration (namely m = −5.5, S-N curve).

5. Conclusions

This study aimed to characterise the short- and long-term behaviour of blind-bolted connectors between steel and FRP plates. Long-term sustained (creep) and cyclic (fatigue) loading experiments were carried out in combination with static shear resistance experiments on single-lap shear joint experiments on M20 blind-bolted Lindapter connectors in a 20 mm thick GFRP plate. It is concluded that the application of blind-bolted connecters is recommended as shear connectors only in applications where hybrid interaction is not required and fatigue loads are of limited extent. This conclusion is based on following findings:

- Blind-bolted connectors demonstrated initial slip of approximately 1 mm at a low shear force (<10 kN), resulting in low shear stiffness of 45 kN/mm. This slip behaviour is unfavourable for fatigue performance in hybrid steel-FRP structural concepts.
- The ultimate shear resistance on average is 154 kN. Bearing failure of the investigated FRP laminate is dominant with a slip displacement at failure of more than 15 mm.
- Blind-bolted connectors subjected to ±20 kN cyclic loading demonstrated bolt failure after 283 thousand cycles on average, whereas FRP bearing failure was observed after 8 thousand cycles of ±40 kN

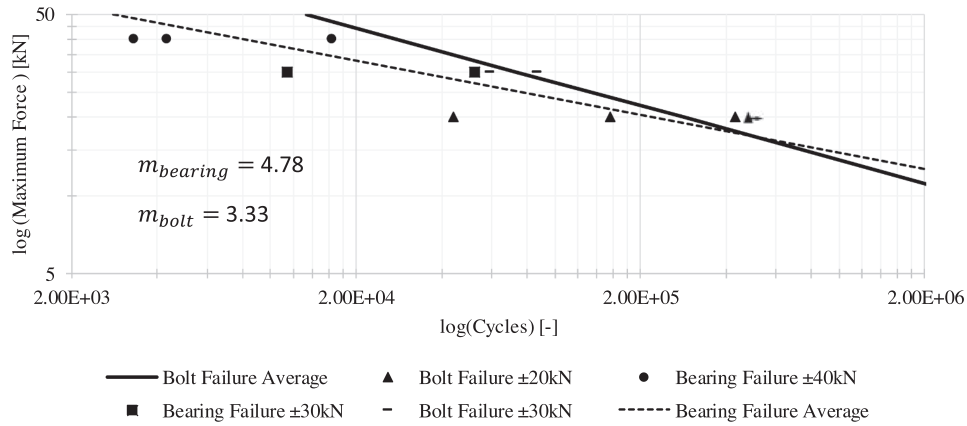

Fig. 9. Preliminary F-N curve (R = −1) for M20 blind-bolted connectors in 20 mm thick multi-directional FRP plate loaded in transverse direction.

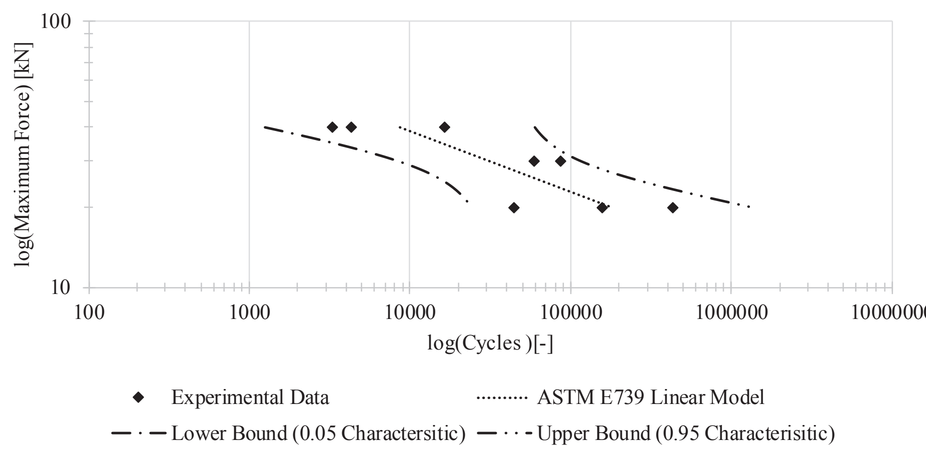

Fig. 10. ASTM E739 statistical analysis.

Table 6
ASTM E739 confidence bands.

Max force [kN]	N lower bound [cycles]	N upper bound [cycles]
20	24,095	1,383,774
30	8267	113,737
40	1256	59,550

on average. In comparison, slip-resistant connectors tested in parallel reached up to 2 million cycles without failure.

- Preliminary F-N curve indicate that blind-bolted connectors can resist large number of cycles at low load ranges. Low load ranges are expected in practice due to low stiffness and slip behaviour of blind-bolted connectors. Further research into high cycle fatigue performance (e.g. >2 million load cycles) at low load levels (e.g. 10 kN) is required to provide information for design of those connectors in non-hybrid applications.
- Blind-bolted connectors showed a 0.15 mm increase in slip displacement, i.e. creep factor of 0.72, when subjected to load equivalent to 25% of ultimate shear resistance for two months. This is the same order of magnitude as for slip-resistant connectors tested in parallel.

CRediT authorship contribution statement

Gerhard Olivier: Investigation, Methodology, Data curation, Writing - original draft, Visualization. **Fruzsina Csillag:** Investigation, Validation, Writing - review & editing. **Elisabeth Tromp:** Conceptualization, Writing - review & editing, Supervision. **Marko Pavlović:** Supervision, Methodology, Writing - review & editing, Project administration, Funding acquisition.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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