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Feasibility of Bolted Connectors in Hybrid FRP-Steel Structures

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Abstract. Due to the low weight and excellent durability of composite materials, Fibre Reinforced Polymer (FRP) decks mounted on steel superstructures are becoming all the more common in engineering practice. Bolted joints are generally used to facilitate connections between an FRP deck and steel girders in road bridges. The connections are subjected to both high magnitude static forces as well as fatigue loading due to overpassing vehicles. With ever increasing traffic on both road and railway bridges, fatigue performance is of critical concern. Bolted FRP joints have been extensively researched in the past under static loading, but less is known about the fatigue and creep behaviour of such joints. Furthermore, little research exists on non-pultruded FRP profiles connected using bolted connections. Therefore, the objective of this research is to investigate connectors' feasibility by means of static, fatigue and creep experiments on four different types of bolted joints comprising mechanical connectors and injection techniques. The study focuses on application in vacuum infused GFRP panels with integrated webs made of multi-directional laminates, connected to steel bridge superstructures. In addition, experimental results are validated by Finite Element Analyses (FEA). Based on the obtained results, the novel injected steel-reinforced resin (iSRR) connector developed at TU Delft shows promising potential in hybrid steel-FRP bridges where good fatigue endurance of the connection and local loads in FRP panel, are required.

Keywords: Bolted connections · Non-slip connections · Fatigue performance · Combined short- and long-term loading · Injected steel reinforced resin

1 Introduction

By utilising benefits from both materials, steel-FRP hybrid structures are a promising candidate in bridge renovation projects where the original deck (steel, concrete or timber) has been deteriorated whilst the main (e.g. steel girders) load carrying structure is unaffected. Due to high strength-to-weight ratio, FRP decks impose minimum additional weight on the existing structure. Low weight also enables prefabrication and

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installation of large deck segments leading to minimum traffic hindrance, which is of significant benefit in bridge infrastructure renovation projects. To implement successful steel to FRP projects, adequate structural performance of the deck-to-girder connection is required. To visualise this scenario, Fig. 1 depicts an FRP deck placed upon steel main load carrying structure of a bascule type movable bridge. In case that hybrid interaction between the FRP deck and the girder is engaged, a non-slip connection is required to obtain reliable shear interaction and sufficient fatigue endurance in a bridge application. In addition, the pull-out resistance of the connectors may play important role as the tensile forces can arise at the connection to flanges of steel girders neighbouring the local wheel loads.

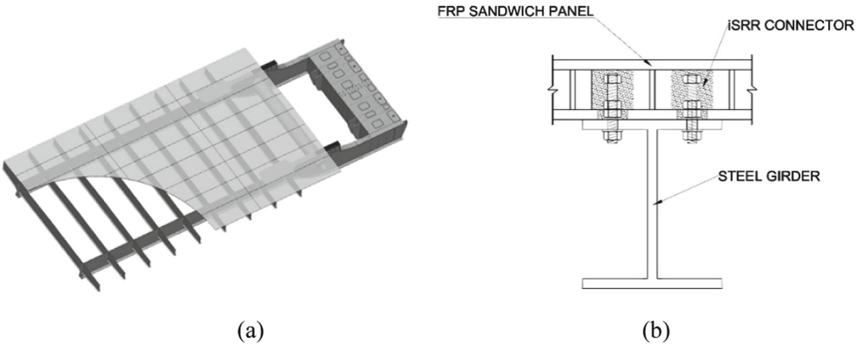


Fig. 1. a) Example of an FRP Deck on a movable bridge; b) iSRR connector between FRP sandwich panel and Steel Girder

Extensive research on adhesive (Keller and Gürtler (2006)) and grouted shear stud connections; (Moon et al. (2002)) between steel and FRP have been performed. In comparison, due to localised load transfer, bolted connections have been examined to a lesser extent. Bolted connections promote demountablity and material reuse of the steel girders and FRP, thereby promoting circular economy. Research performed at TU Delft covers the understanding and characterising of shear and tensile behaviour of existing connectors and the development of innovative connector solutions for FRP decks. The aim is to improve the design life prediction of the connector performance through experimental testing and detailed Finite Element Analysis (FEA). The experimental specimens are designed in such a way as to obtain realistic failure modes as compared to those that would be obtained at the connections between an FRP deck and steel girders in bridges. Finite element models go to deep level of geometrical details at joint level and include damage material models of FRP and steel. Abaqus was used to create the FE Models. Based on the experimental campaign, as well as FEA models, connector behaviour is quantified and application fields are identified.

2 Connector Types and Experimental Approach

The study presented here focuses on four types of bolted connector types used in deck-to-girder connections. Experiments are conducted to investigate the long- and short-term connector performance. A clear distinction will be made between the short-term loading experiments performed by Csillag (2018) as well as the current experimental research campaign of TU Delft to quantify long term-connector performance. The investigated connectors include: two blind bolts (namely Ajax and Lindapter connectors) as well as two non-slip connector types (conventional epoxy injected bolts as well as the injected steel reinforced resin (iSRR) connector). The iSRR connector is a novel, hybrid joining technology developed at TU Delft by Nijgh (2017).

In the **short-term loading experiments**, Ajax, Lindapter and the iSRR connector are investigated. All examined connectors are of 20 mm nominal diameter. The key feature of Ajax and Lindapter connectors is the possibility to be installed from one side from below the FRP deck via predrilled holes by the existence of a foldable washer and expandable sleeve, respectively. In all experiments, connectors are installed in GFRP deck panels with integrated webs and facings made of multi-directional laminates, produced by FiberCore Europe by the vacuum infusion process (fibre volume fraction 54%). The facings of the FRP panels contain the following E-glass fibre composition: [0°/75%; 90°/8.4%/±45°/16.6%] and a matrix comprising of polyester resin. The FRP deck panels are connected to an HEB260B Grade S355 profile as shown in Fig. 2. Push-out experiments are performed to investigate connector performance.

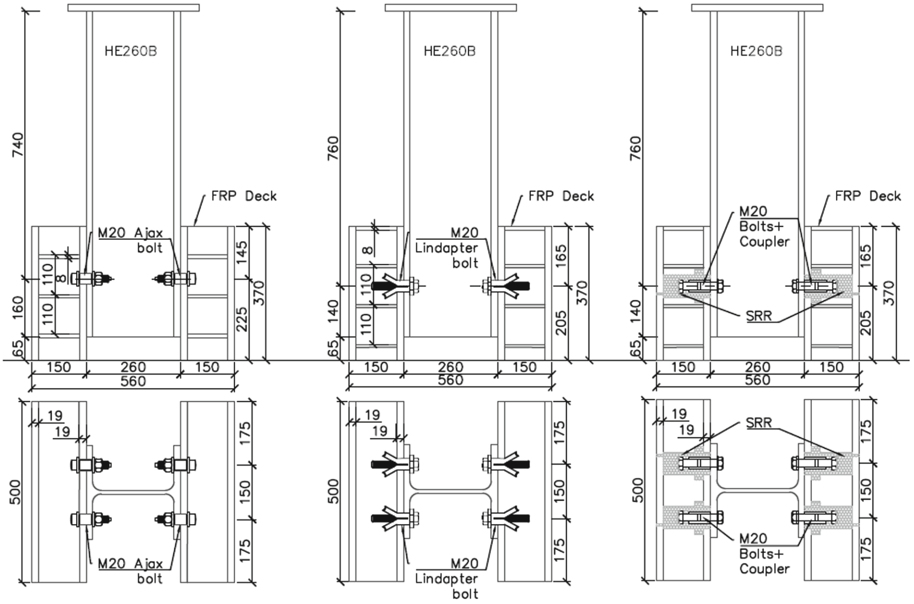
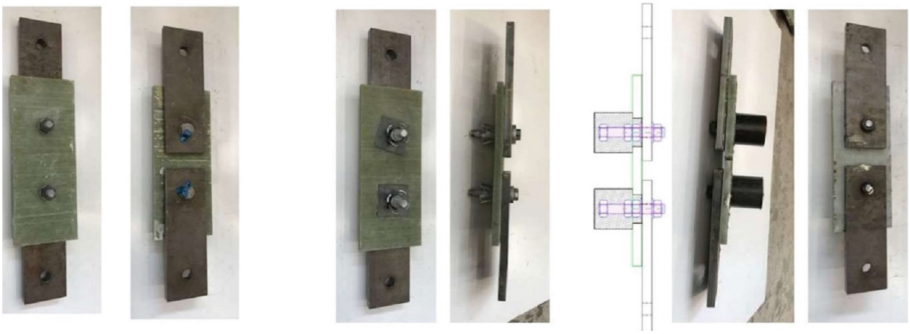


Fig. 2. Push-out experimental configuration (Csillag, 2018)

In the **long-term loading experiments**, two commercially applied connectors (namely epoxy injected bolts and Lindapter connectors), as well as a modified version of the aforementioned iSRR connector are investigated. The conventional injected bolts, as used in steel structures, utilise epoxy resin (Araldite) and are placed in oversized holes. To simplify experimentation, single lap joint (SLJ) specimens were prepared containing a single FRP plate (representing the bottom facing of an FRP deck panel) connected to steel plates (Grade S355). This set-up, as depicted in Fig. 3, facilitates comparisons of connector performance and analysis of failure mechanisms. The fibre composition of the FRP plates [0°/62.5%; 90°/12.5%/±45°/25%] was altered with respect to the aforementioned push-out experiments in order to comply to the recommendations of CUR 96 (2017).



(a) Injected Bolt connectors (b) Lindapter connectors (c) Injected SRR connectors

Fig. 3. Three types of shear connectors for FRP deck panels: specimens comprising of 2 connectors in single-lap shear joint configuration

Separate experimental campaigns will be discussed individually in the subsequent sections of this paper.

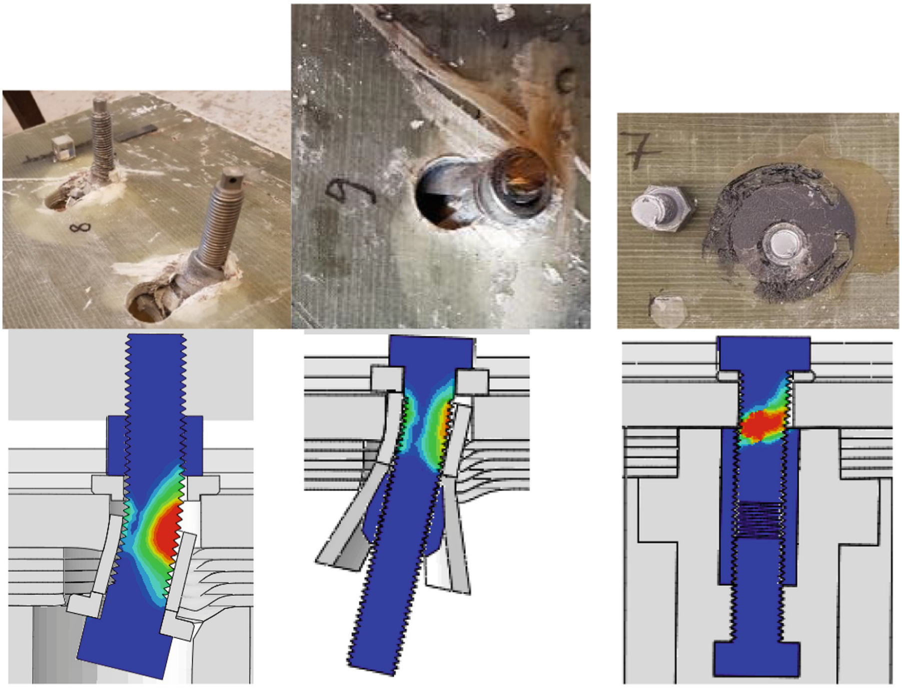
3 Short-Term Loading: Shear and Pull-Out Behaviour

3.1 Experiments

First the feasibility of commercially available blind-bolted vs. the novel iSRR connectors is examined by comparing their shear resistance in segments of GFRP deck panels, as shown in Fig. 4. The Figure depicts the experimentally obtained push-out failure modes as well as major principal plastic strains from Finite Element models (modelled in Abaqus) at the load level prior to failure of each connector.

FRP bearing failure, accompanied by excessive connector yielding, was observed in the specimens with M20 (grade 8.8) blind bolted connectors. Bolt yielding of the Ajax and Lindapter connectors was observed at average shear resistance per connector of approximately 200 kN and 150 kN, respectively. Although being demountable, Ajax shear connectors are impossible to mount again in a second life cycle. Due to extensive connector bending, Lindapter connectors also proved to be non-demountable.

When considering the iSRR connector, bolt shear failure governed ultimate resistance, occurring at approximately 25% lower force as compared to the blind-bolt connectors. The injected piece of the iSRR connector as well as FRP deck panel were undamaged, thereby enabling reuse of the panel in a second life cycle. The iSRR connector was found to possess limited ductility due to the occurrence of bolt shear failure



(a) Ajax Bolts (b) Lindapter connector (c) iSRR connector

Fig. 4. Shear experiments and FEA of connectors in FRP deck panels (Csillag 2018)

at the FRP-Steel interface, as opposed to the quasi-ductile bearing failure and accompanied connector yielding observed in the blind bolted specimens. In second series of experiments, bolts of higher grade (10.9) were used for iSRR which resulted in expected improvement of the ductility allowing more than 6 mm of slip at failure.

In addition to the push out experiments, pull-out experiments were performed on bolted connection specimens using the same connector types. For further details of these experiments, refer to Csillag et al. (2019). Peak loads at the onset of non-linearity (i.e. first observation of FRP cracking and delamination) were measured on average at 58.7 kN, 42.6 kN and 69.3 kN in the Ajax, Lindapter and iSRR connected panels, respectively. Ultimate tensile resistances were measured on average as 95.7 kN; 61.3 kN and 88.4 kN in the Ajax, Lindapter and iSRR connected panels respectively. These results indicate the superior resistance of the iSRR connector to “first crack” as well as force recovery after delamination in the blind-bolted specimens.

The aforementioned results indicate that the feasibility of each connector type relies on its application as well as prevailing design criteria. Advantages per connector type are: shear resistance in terms of Ajax connectors, ease of installation of Lindapter and tensile resistance, non-slip behaviour and demountablity of iSRR connectors.

3.2 Insights from FEA

As depicted in Fig. 4, detailed non-linear FE models (modelled in Abaqus) have been created to analyse shear load transfer mechanisms present in the three investigated connectors. All models include exact modelling of specimen geometry including non-linear material models and were validated by means of comparison to obtained push-out experimental results as performed by Csillag (2018). This modelling approach facilitates detailed analysis of force transfer mechanisms prevalent in each connector type.

In summary, the blind bolt connectors owe their significant slip capacity and shear resistance to bearing failure of the FRP and catenary effects in the connector. Ajax bolts develop the highest connector axial forces during shear loading, due to effective anchorage by the nut and washer. In comparison, FEA demonstrate that Lindapter connectors are not anchored as effectively and subsequently experience bolt rotation which hinder the formation of catenary effects. Finally, load transfer in the iSRR connector was dominated by shearing of the bolt at the FRP-Steel interface as well as crushing of the injected piece. The connector's ultimate strength and slip is limited by brittle bolt failure.

Although the development of axial forces has been shown to be beneficial to static shear resistance in blind bolted connectors, it is hypothesised to likely impair fatigue endurance. To this aim, a second experimental campaign was undertaken to study connector performance under the influence of long-term loading.

4 Long-Term Loading Experiments

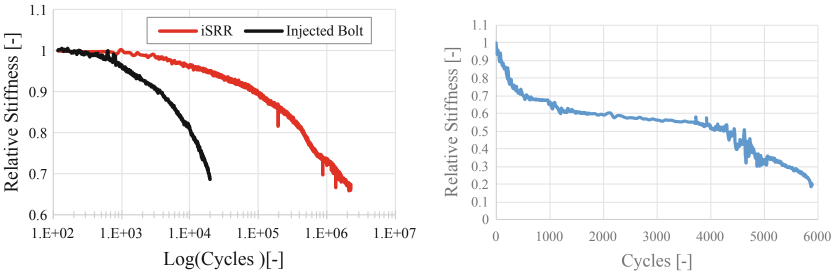
To further quantify connector performance in hybrid steel-FRP bridges, long-term loading experiments were carried out on simplified Single Lap Joint (SLJ) shear specimens. The iSRR connector configuration was altered in this experimental series to enable full preloading of the connector. To facilitate this, the steel coupler and bolts are removed and replaced with a single M20 Grade 10.9 threaded rod. The rod is fastened to the steel plate by means of one and two nuts on the exposed side of the steel plate and within the iSRR injected piece, respectively (as shown in Fig. 3c). As alternative to iSRR as non-slip connector, epoxy Injected Bolts were investigated as a being commercially available. Lastly, Lindapter bolts M20 (grade 8.8), as used in the static push-out experiments, are also tested under long-term loading as readily used connection type where shear load transfer and initial stiffness is not essential, thus no hybrid interaction is accounted between FRP deck and steel structure.

4.1 Experiments

The aforementioned connectors have been tested in monotonic static loading regime until failure to obtain their shear resistance as well as load-slip behaviour including initial stiffness, initial slip and ultimate slip capacity. Individual connector force-slip behaviour was recorded by means of LVDTs. Static resistances ranging between 135 kN and 160 kN were obtained across the three specimen types. Furthermore, the previous limited ductility of the iSRR connector (as recorded in the push-out experiments) has been addressed. This is facilitated by the use of a higher strength grade of the metallic connector (10.9 vs 8.8), enabling an ultimate slip of approximately 8 mm, thereby classified as ductile according to EN 1994-1-1 (2005).

Based on these results, loading range for both the creep and fatigue experiments was selected. A long- term loading level of 40 kN was selected, which equates to 25–30% of the static shear resistance of the SLJ specimens. In order to characterise the connector endurance in fatigue experiments, the relative stiffness of each connector was monitored, defined as the load-slip ratio in each cycle normalised to the load-slip ratio observed in the first load cycle.

Figure 5a shows characteristic stiffness degradation vs. load cycles of “non-slip” connector types, namely iSRR and Injected Bolt. One results out of six specimens tested per each type are shown. These connectors were loaded by cycles of ±40 kN until an increase in slip displacement of 0.3 mm was reached. This displacement increase limit was adopted from Annex G of EN 1090-2 (2008), as defined for non-slip connection in steel structures. Such stringent additional slip displacement criterion was not imposed to the blind-bolted “slip type” connectors, namely Lindapter connectors, due to their initial slip behaviour. The criterion used in this case was either bolt fracture or rapid increase of slip due to excessive bearing deformation in FRP plate. iSRR connectors were able to sustain in average 2.000.000 load cycles, whereas Injected Bolts on average sustained 25.000 cycles until additional slip displacement of 0.3 mm, equivalent to approx. 35% of connection stiffness degradation, as shown in Fig. 5a. This is due to load transfer in iSRR through reinforced injection material possessing higher stiffness than the regular polymeric-only injection material, allowing for larger hole diameters which in turn reduces stress concentrations in facing of FRP panel. None of the non-slip connectors suffered fracture of bolt or injection of FRP due to fatigue loading up to 0.3 mm additional slip criterion. Lindapter connectors subjected to the same shear load range ±40 kN failed by excessive bearing in 8.000 cycles on average, as shown on example results in Fig. 5b. A twice lower load range on Lindapter connectors resulted in bolt head fracture after 280.000 cycles on average.



(a) iSRR and Injected Bolts – non-slip connection; (b) Lindapter connectors – slip connection

Fig. 5. Shear stiffness degradation as indication of fatigue performance of the connectors

Creep tests comprised of maintaining a constant 40 kN load. After two months of loading, it was found that Lindapter and Injected Bolt connectors on average showed a 46% and 72% higher creep displacement, respectively, as compared to the iSRR specimens.

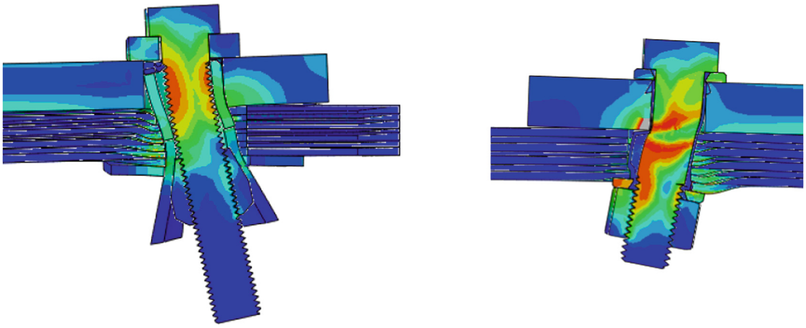
When considering the effect of prior sustained loading before cyclic loading, it was found that iSRR connectors reached the 0.3 mm criterion under cyclic loading 20% sooner. Due to the low number of achieved cycles as well as scattering of experimental result, no clear influence of prior sustained loading on fatigue performance of Injected Bolts was discernible.

The residual static resistance of SLJ samples of iSRR connectors after subjection to combined long-term loading (64 days sustained 40 kN + 2 million cycles of ±40 kN load) was unchanged compared to the static resistance obtained under short-term loading only. On the other hand, residual static resistance of Injected Bolts after same long-term loading regime was reduced in average by 30%. This result further illustrates the potential of the iSRR connector to be used in applications where a high fatigue endurance is required.

Based on the obtained results, the following application fields are recommended per connector type: the Lindapter connector is to be selected as blind-bolted connector to be used in connection of FRP decks in non-hybrid and non-fatigue applications, such as pedestrian and cyclist bridges. The other two connectors (Injected Bolts and the iSRR connector) are potential candidates for non-slip connection in hybrid construction where good fatigue performance is required. Injected Bolts were shown to be less resistant under cyclic loading and display higher creep displacements under sustained loading as compared to the iSRR connector. Furthermore, by enabling full preloading onto steel alone and ensuring service loads are kept below the applied preloading force, the long-term behaviour of iSRR connector is superior.

4.2 Insights from FEA

In the same manner as performed for the push-out experiments, detailed non-linear FEAs (examples shown in Fig. 6, modelled in Abaqus) were prepared to further understand the mechanism of force transfer per connector type.



(a) Lindapter Connector

(b) Injected Bolt

Fig. 6. FEAs of single lap joint tests

The FEAs demonstrate that the iSRR connector engages in force transfer by means of friction via the preloaded threaded rod to steel package, as opposed to shear load transfer in the Injected Bolt and Lindapter connectors. In addition, the iSRR connector experience a minimal loss in axial preload when subjected to the 40 kN shear load level, as applied in the long-term loading experiments. In this load range the iSRR connector relies on force transfer by means of friction, thereby being comparable to the behaviour of a preloaded bolt in steel structures. Injected Bolts and Lindapter bolts are unable to be effectively preloaded due to the presence of FRP within the clamping package, and as such rely on force transfer by means of shear loading of the connector. Under the applied 40 kN shear long-term loading, non-negligible axial forces develop in the Lindapter and Injected Bolt connectors due to catenary effects due to bolt inclination, as shown in Fig. 6.

5 Conclusions and Outlook

FRP offers great potential to reduce weight, maintenance costs and increase lifetime in new built and renovation projects in highway bridges. The current challenge restricting wider application is the lack of knowledge and efficient solutions for non-slip connections to FRP. This paper has summarised the research performed at TU Delft into performance of connector types in steel to FRP connections in hybrid and non-hybrid bridges. Two blind-bolted solutions available on the market, Lindapter and Ajax, providing connection with initial slip are compared to two non-slip connector types, the regular injected bolts and novel preloaded connectors injected with steel-reinforced resin (iSRR) developed at TU Delft. iSRR connectors show to be able of achieving large initial stiffness and shear resistance whilst enabling large execution tolerance and good long term cyclic (fatigue) and sustained load (creep) performance.

From the short-term experiments, Ajax connectors offer superior shear resistance due to development of catenary effects, whereas Lindapter bolts offer less shear resistance although ease of installation. The iSRR connector proved to be demountable, possess the highest resistance prior to the onset of non-linearity in pull-out experiments amongst the investigated connectors.

Non-slip joints are required in steel-FRP bridge applications where hybrid interaction between the deck and steel substructure is inevitable and/or desirable. In the long-term loading experiments, iSRR connectors demonstrated superior behaviour compared to Injected Bolts, approx. 100 times more cycles to slip and half creep deformation at the same load level. The existing blind-bolted solution (i.e. Lindapter connector) demonstrated initial slip behaviour which excludes usage in steel-FRP hybrid structural concepts. However, this does not limit their usage in non-hybrid structures due to their application in a number of existing and future built structures.

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