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Static and fatigue behavior of bonded, bolted and hybrid FRP joints

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Abstract: *An experimental investigation on the static and fatigue behavior of adhesively-bonded, bolted and hybrid bonded/bolted FRP double-lap joints was conducted at EPFL-CCLab. The effects of the adhesive type (stiff or flexible) on the bonded joints and the fiber architecture (uni- or multidirectional) of the adherends on the bolted joints were examined in the static experiments. Both behaviors, static and fatigue, of the hybrid joints, were compared to those of only bonded and only bolted joints of similar dimensions.*

In the static case, bonded joints comprising a flexible acrylic adhesive exhibited a ductile response compared to those with a stiff epoxy adhesive; similarly, as bolted joints with multi-directional fiber architecture did compared to the unidirectional cases. The resistances of the hybrid joints composed of ductile adhesive and adherends with multi-directional fiber architecture corresponded to almost the full summation of the resistances of the bonded and bolted connection parts. The fatigue behavior of hybrid joints was much improved compared to that of only bonded and only bolted joints. The fatigue life of the bonded and hybrid joints was always reached at almost the same ultimate failure displacements. In the hybrid joints, the increase of the adhesive displacements was retarded by the bolts, which extended the fatigue life since more cycles could be sustained to attain the same ultimate failure displacement.

Keywords: bonded joints; bolted joints; hybrid joints; static resistance; fatigue.

1 Introduction

Pultruded fiber-reinforced polymer (FRP) profiles have been the focus of increasing interest as structural members in recent structural engineering applications, such as FRP truss structures or FRP bridge decks, because of their high strength-to-weight ratio, superior mechanical and chemical resistance, and economical industrial production [1]. Since joints are usually the weakest part of load-bearing members, effective joint design is the key to fully utilizing the strength of FRP members [2]. Adhesively-bonded and bolted joints are the two main techniques for connecting FRP members [3]. Adhesively-bonded joints normally exhibit higher stiffness, efficiency, and longer fatigue life [4]; however, bolted joints are easier to assemble and disassemble [5]. To combine the advantages offered by these two joint techniques, hybrid joints, i.e. bonded-bolted joints, have attracted increasing attention in different fields of application [6].

A controversial point of hybrid joints is whether the combined bonded and bolted connections can share the load. In previous studies [7], stiff adhesives were used for hybrid joints and no load-sharing was observed, i.e. hybrid joints did not improve the bonded joint resistance. Recently, load sharing between bonded and bolted connections was however achieved by using more flexible adhesives due to large deformations of adhesive [8].

Since the live load-to-weight of FRP structures is often high, particularly in the case of lightweight FRP road bridges subjected to heavy truck loads, the fatigue behavior of such structures, and their joints in particular, represent one of the most important concerns. The fatigue behavior of only bonded and bolted joints have been widely investigated compared to hybrid joints [8,9]. The fatigue life of hybrid joints was the summation of that of the bonded and bolted connections if stiff adhesives were used [9]; however, the life was longer than the summation if flexible adhesives were applied[8].

Although several investigations of hybrid joints have been carried out concerning the static behavior with improved load-sharing, a full summation of the bonded and bolted connection resistances has not yet been achieved and the fatigue behavior of such joints was much less investigated. The aims of the present work were therefore 1) to achieve a full summation of the bonded and bolted connection resistances in hybrid joints by appropriate selection of adhesive and adherend materials, and 2) to characterize the fatigue behavior of hybrid joints, in terms of load-cycle (*F-N*) curves and cyclic displacement variations, and compared to those of only bonded and bolted joints.

The work thus experimentally investigated the static and fatigue behavior of bonded, bolted and hybrid joints. Two different adhesives (a stiff and a flexible one) and two different FRP adherends (with uni- and multidirectional architectures) were selected for hybrid joints to obtain optimum hybrid combinations. Several different load levels were selected for bonded, bolted and hybrid joints for the fatigue experiments to establish the *F-N* curves. The loading frequency for bonded and hybrid joints was varied to maintain the same loading rate for the adhesive. The cyclic-displacement was derived from the load-displacement loops measured during fatigue cycles.

2 Experimental program

The experimental work comprised two main objectives, 1) to investigate the effects of the fiber architecture and adhesive type on the resistance of hybrid joints, to determine the most effective combination; 2) to derive the *F-N* curve of hybrid joints and compare it to those of only bonded and bolted joints of the same dimension.

2.1 Materials

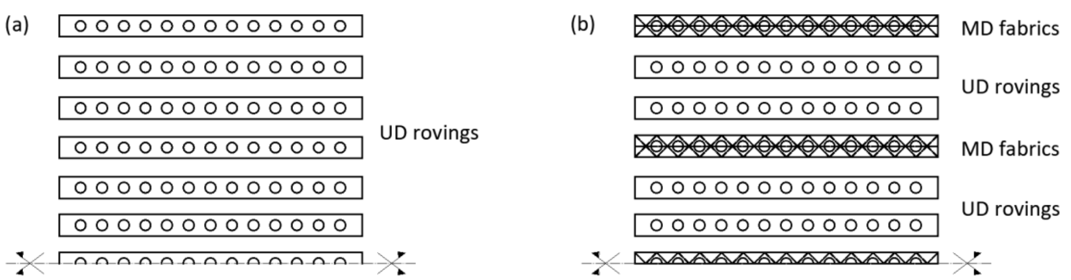

Fig. 1. Fiber architecture of (a) unidirectional, UD and (b) multidirectional, MD adherends.

Basalt-FRP (BFRP) pultruded plates were used as adherends with a thickness of 4.15 mm. Two different fiber architectures were considered, designated UD and MD, as shown in Fig. 1. The total fiber volume fractions were 66% for UD and 68% for MD, individually; the volume fractions in the latter case for different directions of the fiber orientation were 0°/±45°/90°=70/20/10 %. More detailed information can be found in [10]. The basic mechanical properties of BFRP adherends are listed in Table 1.

Stainless steel, 12.9-grade bolts with 1080 MPa yield strength and 1200 MPa ultimate strength were selected. An acrylic adhesive exhibiting high failure strain [11], designated ADP, and an epoxy adhesive with low failure strain [12], indicated EP, were used. The mechanical properties of these two adhesives are listed in Table 1.

Table 1. Mechanical properties of BFRP adherends and adhesives.

Materials	Mechanical properties		
	Tensile strength (MPa)	Tensile modulus (GPa)	Failure elongation (%)
UD adherends	1212 ± 23	51.4 ± 0.9	2.36 ± 0.02
MD adherends	971 ± 25	41.7 ± 1.8	2.33 ± 0.04
ADP adhesive	12 ± 4.3	0.21 ± 0.05	59.8 ± 14.5
EP adhesive	38 ± 2.1	4.6 ± 0.14	0.83 ± 0.13

2.2 Specimen geometry and preparation

Symmetric double-lap joints were considered to minimize the effects of the load eccentricity. The specimen dimensions of the bonded and hybrid joints were derived from the design of the bolted joints with an 8-mm bolt diameter, as shown in Fig. 2. The thickness of the adhesive layer for bonded and hybrid joints was 2 mm. The detailed preparation and fabrication for the joints was reported in [10].

2.3 Experimental set-up and instrumentation

2.3.1 Static experiments

Table 2. Overview of static experiments and results for bonded, bolted and hybrid joints.

Joint type	Specimen denomination	Adherend	Adhesive	Ult. Failure disp. (mm)	Ult. Failure load (kN)
Bonded joints	A-U-E	UD	EP	0.012 ± 0.004	19.3 ± 1.0
	A-U-A	UD	ADP	5.48 ± 0.32	43.7 ± 1.3
Bolted joints	B-U	UD	-	1.56 ± 0.07	11.0 ± 0.2
	B-M	MD	-	9.45 ± 0.21	20.9 ± 0.4
Hybrid joints	H-M-E	MD	EP	9.52 ± 1.47	23.3 ± 1.4
	H-M-A	MD	ADP	5.24 ± 0.13	56.8 ± 3.4

The static experiments for joints were conducted on a *W+B* 200 kN machine at laboratory temperature (15 ± 5℃). Monotonic tensile loading was applied until the failure of the specimens occurred. A video extensometer camera was used to measure the joint displacements during loading [10]. An overview of the series of static experiments for bonded, bolted and hybrid joints is listed in Table 2. The designation for the joints is as follows: the first term indicates the joint type; the second denotes the fiber architecture of adherends; and the last one represents the adhesive type. Three specimens were examined for each configuration.

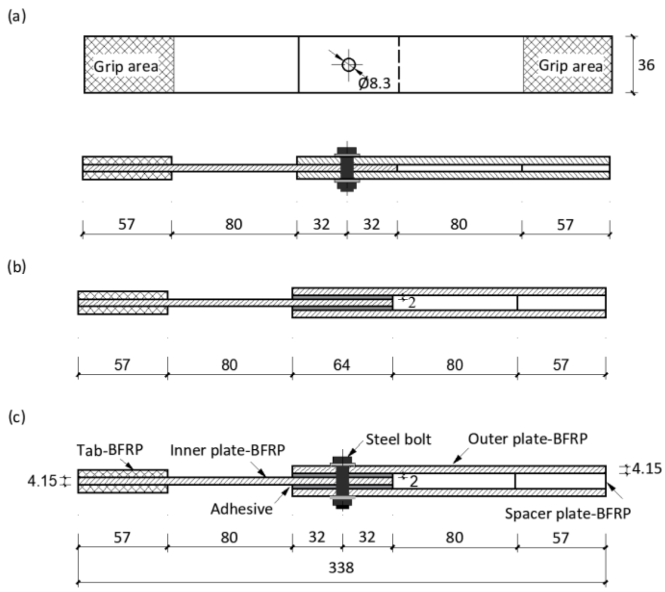

Fig. 2. Joint dimensions: (a) bolted joint; (b) bonded joint; (c) hybrid joint (dimensions in (mm)).

2.3.2 Fatigue experiments

The fatigue experiments were performed according to ASTM D3479 on an Instron 100kN machine. All experiments were conducted under load control, in a sinusoidal loading waveform with constant amplitude and load ratio, $R = F_{min}/F_{max} = 0.1$. A constant fatigue loading rate of 75.6kN/s was selected for the bonded and hybrid joints and a constant loading frequency of 5Hz was determined for the bolted joints. Seven load levels were selected from 8.4 to 29.5 kN for the bonded joints, and six load levels for the bolted joints from 8.4 to 15.8 kN and the hybrid joints from 14.2 to 34.0 kN, respectively, to cover fatigue lives from 10^2 to $2{\cdot}10^6$ cycles. The fatigue loading was applied until failure or up to 2 million cycles.

The load-stroke responses and number of cycles were recorded by the Instron machine. DIC was used to measure the variation of the joint displacements by recording images at 100Hz for specified cycle intervals.

Three specimens were examined at each selected load level and all fatigue experiments were performed in the same air-conditioned laboratory environment (T = 24 ± 2°C, RH = 45 ± 5%) to minimize the effects of ambient temperature changes.

3 Experimental results and discussion

3.1 Static experiments

3.1.1 Bonded joints

The effects of the adhesive type of EP and ADP on the load-displacement responses of the bonded joints are shown in Fig. 3. The EP specimens exhibited a linear and brittle behavior while the ADP specimens showed a bilinear and highly ductile response. Linear elastic behavior was observed up to 64% (on average) of the ultimate failure load, followed by a yield stage and subsequent slight hardening, attributed to the stretching of the molecular chains. In addition, the ultimate failure load of the ADP joints was 2.3x higher (on average) than that of the EP joints.

3.1.2 Bolted joints

The effects of fiber architecture of UD and MD on the load-displacement responses of the bolted joints are shown in Fig. 3. Compared to the UD cases, MD bolted joints exhibited significantly (almost two times) increased ultimate failure loads and much larger deformation capacity, as listed in Table 2. The improved joint behavior was attributed to a change in failure mode from a brittle splitting failure in the UD cases to a progressive bearing failure in the MD joints.

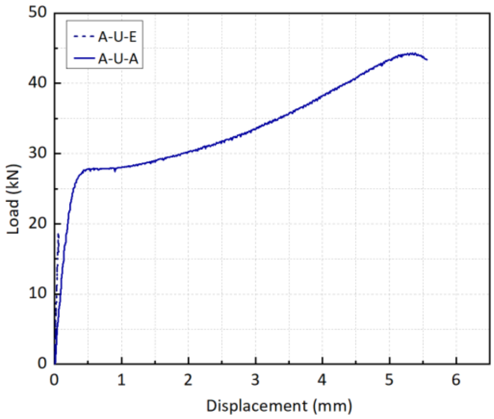

Fig. 3. Load-displacement responses of bonded joints with different adhesives.

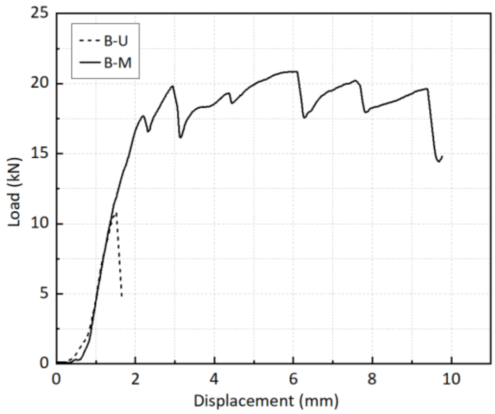

Fig. 4. Load-displacement responses of bolted joints with different fiber architecture.

3.1.3 Hybrid joints

3.1.3.1 MD-EP hybrid joints

The load-displacement response of a typical MD-EP hybrid joint comprising MD adherends and EP adhesive is shown in Fig. 5 and compared with the corresponding MD bolted and EP bonded joints. The hybrid joints exhibited a two-stage behavior, i.e., no load sharing between the bonded and bolted connections occurred. In the first stage, the applied load was only transferred by the adhesive connection due to its much higher stiffness. Subsequently, adhesive failure occurred, and the load dropped to the level of the bolted joint at this displacement. In the second stage, the entire load was transferred by the bolted connection until its ultimate bearing failure with large deformation.

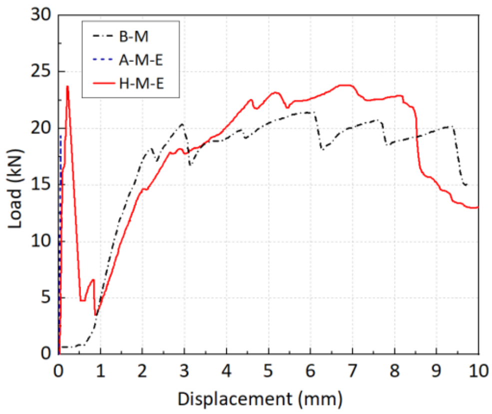

Fig. 5. Load-displacement responses of MD bolted, EP bonded and MD-EP hybrid joints.

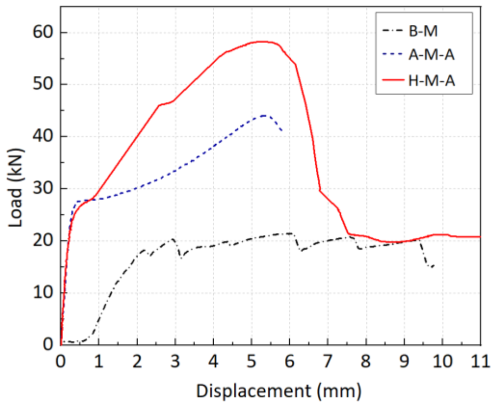

Fig. 6. Load-displacement responses of MD bolted, ADP bonded and MD-ADP hybrid joints.

3.1.3.2 MD-ADP hybrid joints

The load-displacement response of a representative MD-ADP hybrid joint, composed of MD adherends and ADP adhesive, is compared to the responses of MD bolted and ADP bonded joints in Fig. 6. Until the bolted connection was activated, the stiffness of the hybrid joint was governed by the bonded connection, and no load sharing had yet occurred. Subsequently, full load sharing was initiated and continued, and the joint stiffness increased accordingly up to the ultimate failure load, which was almost the summation of the bonded and bolted connection resistances (see mean values in Table 2, -8.7%). After the failure of the adhesive connection, the load dropped to the level of the bolted connection, which continued to sustain the load until its ultimate failure.

3.2 Fatigue experiments

3.2.1 Fatigue life

The fatigue maximum load, F_{max}, against fatigue life, N_f, for bonded, bolted and hybrid joints, on a logarithmic scale, is shown in Fig. 7; a classic power-law relationship, expressed by Eq. (1), was used to fit the *F-N* experimental data:

$$F_{\max} = F_0 N_f^{-k} \quad (1)$$

where F_0 and k are the model parameters obtained from a regression analysis. The model parameters for bonded, bolted and hybrid joints are listed in Table *3*. Specimens survived the 2 million cycles were indicated with a right-facing arrow and were not included in the regression analysis.

The fatigue resistance of the hybrid joints was higher than that of the bonded and bolted joints, and was affected mainly by the bonded connections, as demonstrated by the similar slopes of the *F-N* curves. Bolted joints showed lower fatigue resistance, however, the decreasing rate of the *F-N* curve was much less than in the bonded and hybrid joints.

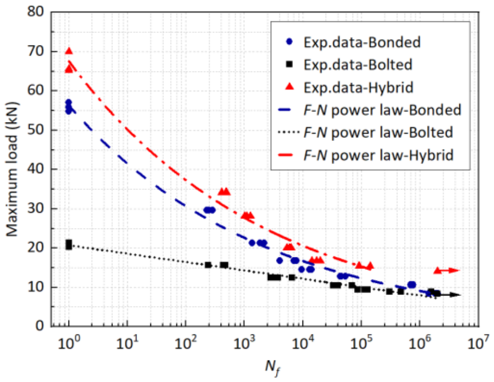

Fig. 7. Experimental fatigue data and fitting F-N curves for bonded, bolted and hybrid joints.

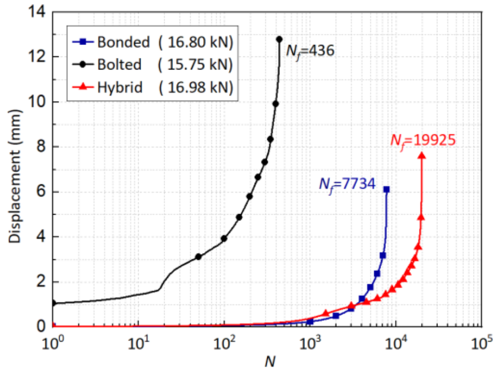

Fig. 8. Cyclic displacements versus normalized number of cycles at a selected load level of 16 kN for bonded, bolted and hybrid joints.

Table 3. Model parameters of F-N fitting curves for bonded, bolted and hybrid joints.

Joint types	F_0	k
Bonded joints	56.32	0.130
Bolted joints	21.28	0.065
Hybrid joints	67.98	0.129

3.2.2 Cyclic displacements

The variation of the cyclic displacements versus the normalized number of cycles during fatigue for bonded, bolted and hybrid joints at a selected load level of 16 kN was compared in Fig. 8. The fatigue life of the hybrid joints was longer than the summation of that of the bonded and bolted joints due to the loading sharing between them. As reported in the previous work [13], all bonded joints failed at a similar failure displacement when the molecular chains were fully stretched. The failure displacement of the hybrid joints was similar to that of the bonded joints, i.e., hybrid joints failed when the failure in the adhesive occurred. However, the increase of displacement of the hybrid joints during fatigue was retarded by the bolts. This limitation extended the fatigue life since more cycles could be sustained to attain the same ultimate failure displacements.

4 Conclusions

An experimental investigation of the static and fatigue behavior of bonded, bolted and hybrid joints was conducted. The effects of fiber architecture and adhesive type on the load-bearing behavior of hybrid joints were investigated to determine the optimum combination. The *F-N* curves for bonded, bolted and hybrid joints were established. The conclusions of this work are summarized as follows:

(1) MD bolted joints significantly increased the joint resistance and deformation capacity compared to the unidirectional cases; ADP bonded joints exhibited a highly ductile response compared to EP cases.

(2) Hybrid joints comprising EP adhesive failed to achieve load sharing between bonded and bolted connections, however, the resistance of hybrid joints comprising the ADP adhesive corresponded to almost the full summation of the resistances of the bonded and bolted connection parts due to almost equal and large deformation capacities.

(3) The fatigue resistance of hybrid joints comprising the ADP adhesive was much improved compared to that of bonded and bolted joints due to the load sharing behavior; it was mainly dependent on the bonded connections.

(4) Hybrid joints failed at the same displacement as bonded joints. The increase of displacement was retarded by the bolts in the hybrid joints and the fatigue life was thus extended until reaching the same ultimate failure displacement.

5 References

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