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Effect of FRP-to-steel bonded joint configuration on interfacial stresses: Finite element investigation

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ABSTRACT

Externally bonded fibre-reinforced polymer (FRP) composites can be applied to strengthen and repair existing steel structures. In order to understand and quantify the behaviour of the bonded interface, researchers have conveniently tested FRP-to-steel joint assemblages. Both single- and double-shear joints of varying boundary conditions have been tested to date in which either the steel or FRP components have been loaded. In addition, the material and geometric properties of the joint materials have been varied and such variation in properties and test configuration will cause variation in the distribution and magnitude of interfacial stresses. This study presents the results of finite element simulations of the interfacial stresses of several FRP-to-steel joint configurations considered by researchers to date. Numerical simulations of interfacial stresses are also conducted on an FRP-strengthened I-beam and several key locations are examined in greater detail such as at the plate end, an intermediate fatigue induced crack, and a yielded zone. The beam stresses are compared with the stresses from the joint models and then joint configurations are identified which best capture the interfacial stress distributions at various positions along the length of the beam.

1. Introduction

The external bonding of high-strength, light-weight fibre-reinforced polymer (FRP) composites to existing steel structures offers an effective and rapid repair and strengthening solution. FRP composites have been applied to steel structures in different manners over the years, namely (i) strengthening of flexural members (e.g. steel beam and girders, composite steel-concrete members), (ii) strengthening of compression members (e.g. circular and square hollow sections, concrete filled tubes), (iii) fatigue strengthening, and (iv) strengthening of connections. State-of-the-art reviews have also been published over the years i.e. [1–3], however, limited design guidance has been developed to date [4,5]. The reader is directed to review papers as well as the relevant general scientific literature for a deeper treatment of the application of FRP composites to steel construction materials.

In the majority of strengthening applications, the bond between the externally bonded FRP and the steel substrate is of fundamental importance. In order to investigate the bonded interface, researchers have resorted to testing FRP-to-steel joint assemblies of varying configurations e.g. [6–11]. The results of such joint tests can then be generalised in the form of bond strength and bond stress-slip models e.g. [2,11]. These models are important as they are useful for the design and analysis of FRP-strengthened steel members such as beams. Central to the development of these models though are the distributions of elastic shear and normal stresses at the FRP-to-steel interface [11]. Such testing and subsequent model development is therefore convenient and popular. The reader is referred to the literature pertaining to interfacial stress distributions e.g. [12,13] as well as bond strength and bond-slip modelling e.g. [14,15] for further information.

In order to characterise the bonded FRP-to-steel interface, single-shear e.g. [6,10] and double-shear e.g. [7–9] joint configurations, which are shown schematically in Fig. 1, have been tested. While the number of shear planes of test joint configurations can vary, the position of application of load as well as the test joint boundary conditions can also vary. For instance, load may be applied directly to the FRP plate while the steel substrate is suitably restrained e.g. [6]. Alternatively, load may be applied directly to the steel substrate and the FRP plates are then indirectly stressed via elongation of the steel e.g. [9]. Zhao and Zhang [2] in turn conveniently categorised the different test configurations as (i) Type 1: load indirectly applied to FRP and steel plate in a beam, (ii) Type 2: load directly applied to steel element without gap, (iii) Type 3: load directly applied to steel element with gap, and (iv) Type 4: load applied directly to FRP. Each test arrangement and its accompanying material and

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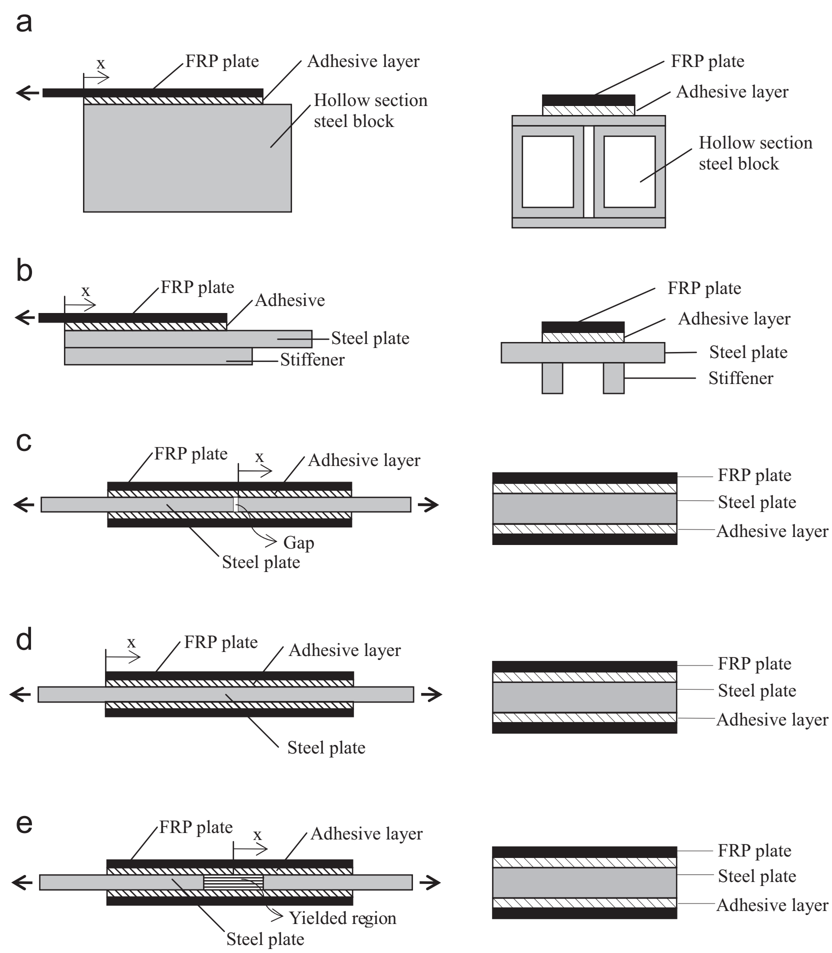

Fig. 1. FRP-to-steel joints: elevations and sections. (a) Xia and Teng [6]; (b) Kim et al. [10]; (c) Fawzia et al. [7]; (d) Haghani [9]; (e) Al-Emrani and Kliger [16].

Table 1
Steel, FRP and epoxy material properties and geometry.

Material	Joint	Width (mm)	Thickness (mm)[a]	Elastic modulus (MPa)	Yield Stress or Tensile Strength (MPa)	Comments
Steel	Xia and Teng [6]	118	12[b]	NA	NA	NA
	Kim et al. [10]	100	10[b]	212,000	332	Mild steel
				181,000	462	Stainless steel
	Fawzia et al. 7]	50	6; 10	NA	430–532	Mild steel
	Haghani [9]	30	10	210,000	510	S355
	Al-Emrani and Kliger [16]	36	10	NA	281	NA
FRP	Xia and Teng [6]	50	1.2	165,000	NA	Pultruted plate
	Kim et al. [10]	35	1.4	230,000	3367	Pultruted plate
	Fawzia et al. [7]	50	0.19×3 layers	230,000[c]	2675	Sheet
			0.176×3 layers	552,000[c]	1175	Sheet
	Haghani [9]	30	2.4	165,000	3100	SIKA (pultruted)
			4	383,000	1100	STO (pultruted)
	Al-Emrani and Kliger [16]	25	1.2	155,000	1932	–
			1.43	174,000	1855	–
			1.95	383,000	1252	–
			4.4	362,000	1252	–
Epoxy	Xia and Teng [6]	50	0.875–6.12	4013	22.53	–
				10,793	20.48	–
				5426	13.89	–
	Kim et al. [10]	35	1.3–1.5	8886	27	–
	Fawzia et al. [7]	50	0.224	1901[c]	28.6	Araldite 420
				9892[c]	24	Sikadur 30
				2028[c]	24.8	MBrace
	Haghani [9]	30	3.4	4500	32	Sika 330
			2	7000	26	STO 567
	Al-Emrani and Kliger [16]	25	2	14,000	32	–
				6500	24	–

NA = not available.

[a] Steel and FRP thicknesses nominal, epoxy thicknesses measured.

[b] FRP is bonded onto this flange plate.

[c] Extracted from Fawzia [18].