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BOND PERFORMANCE OF CFRP/STEEL COMPOSITES: STATE –OF-THE-ART-REVIEW

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Abstract: Over the past decade, CFRP (Carbon Fibre Reinforced Polymer) has been established as an excellent strengthening material to use in the metallic structures. Performance of CFRP strengthened steel members is directly dependent on the quality and the integrity of the adhesive bond. However, the insufficient knowledge on the bond behaviour of the CFRP/steel bonded joints is the major drawback in the lacking of real world applications of this system. Bonding procedure, including the surface preparation, different loading conditions and environmental conditions experienced can critically affect the bond behaviour and its performance. Studies have shown that dynamic loadings (fatigue/impact) can contribute to the strength and stiffness reduction of the bond while aggravating the results in severe exposed conditions. Also, these structures are frequently exposed to environmental conditions such as temperature variations, humidity conditions, UV radiation and marine environment. The consequence is severe when these exposure conditions are combined. This paper presents a state of the art review on bond performance of CFRP strengthened steel members for different load effects.

Keywords: bond performance; CFRP; durability; environmental conditions; loading; Steel; strengthening

1. Introduction

Most of the steel structures like bridges and infrastructure buildings in locally and all over the world are approaching their design lifetime or rather exceeded. Besides, these structures are required to carry more loads and traffic than they have been designed. Complete/ partial restoration is costly, time consuming and disturb the functionality of the structure. Therefore, strengthening mechanisms are encouraged to improve the strength of the damaged steel members and expand lifetime of the structure. A traditional method of strengthening is to weld steel plates to the selected members and this method requires a lot of time and labour resources. Moreover, as the steel plates are heavy, the installation and transportation is difficult and increase the dead weight of the structure. Because of these aforementioned disadvantages, alternative techniques are promoted and Fiber Reinforced Polymers (FRP) are found to be the best solution.

Although there are various types of fibers available (e.g: Glass, Aramid, Basalt etc.), Carbon fibers have been widely used in fabrication of fiber Reinforced Polymer for several reasons such as high strength and elastic modulus, excellent fatigue performance and corrosion resistance [1]. CFRP sheets and laminates are the frequently used FRP forms in the strengthening process and the different types of CFRP are available based on the modulus of the elasticity (Table 1). Adhesive bonding is chosen over any other mechanical fastening methods to bond these two different materials (CFRP and steel) in order to gain a uniform stress distribution and eliminate local stress concentrations [2].

Table 1: Moduli of elasticity of CFRP

Form of	Modulus of Elasticity (GPa)

CFRP		
CFRP Sheets (230–640 GPa [3])	Low Modulus (LM) CFRP	< 100 GPa (E_{cfrp} < 0.5 E_{steel})
	Normal Modulus (NM) CFRP	100 – 200 GPa (0.5 E_{steel} < E_{cfrp} < E_{steel})
	High Modulus (HM) CFRP	200 – 400 GPa (E_{steel} < E_{cfrp} < 2 E_{steel})
	Ultra – High Modulus (UHM) CFRP	≥ 400 GPa (≥ 2 E_{steel})
CFRP laminates [4]	Normal Modulus (NM) CFRP	100 – 250 GPa
	High Modulus (HM) CFRP	> 250 GPa

Application of CFRP in retrofitting concrete structures has advanced to a promising method with the development of standards and regulations (ACI 440.2R– 08, [5]. Yet the applicability of this technique to metallic structures has not progressed that much. The main reason is the lack of knowledge on the bond behaviour between the CFRP composite and the metallic substrate. Unlike for the concrete substrates, de-bonding scenarios and the failure modes are different in the CFRP patched steel members. The failure mode of the CFRP strengthened concrete member is more often identified to be a cohesion failure (adhesive layer failure) of the concrete substrate. But the failure modes of a CFRP strengthened metallic surface can be more complex than that of a concrete substrate (Fig.1). Therefore, substituting results of FRP/Concrete composite system directly into the CFRP/steel composite system is not appropriate. Adhesive joint being the weakest link of the CFRP/steel system, the effectiveness of this strengthening technique is mainly dependent on the quality, integrity and the durability of the bonding.

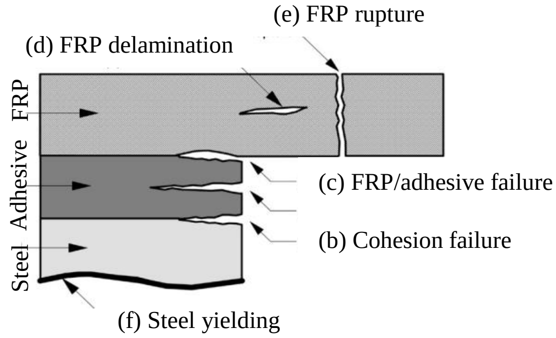


Fig. 1. The failure modes of a CFRP strengthened Steel joint [3]

There are quite a few numbers of review articles published regarding FRP strengthening system and all of them have taken into account the advancement of knowledge on bond behaviour between CFRP and steel. In 2002, Hollaway and Cadei [6] addressed, proposed surface preparation method of the two adherends, load transfer mechanism between two materials and the durability of the joint. In 2004, Stratford, Cadei, and Holloway published CIRIA Design guide (C595) [7] which categorized the FRP strengthening system in four major stages; 1. Materials involved, 2. Detailed design, 3. Installation and 4. Operation. State-of-the-art- review published by Zhao and Zhang, 2007 [3], looked attentively at the bond test methods, possible failure modes in CFRP/Steel composite system, approaches to predict the bond strength and bond slip models. Teng et al, 2012 [8] had also provided with an informative literature which studied the bond behaviour between CFRP and steel. Al – Mosawe et al, 2013 [9] had summarized quite a bit of significant work on the information regarding bond characteristics between steel and CFRP laminate when they are subjected to static and impact loading. In 2014, Zhao et al [10] published a literature looking at the effects of dynamic loading and the environmental conditions on the bond performance. Further, to assess the environmental durability of the strengthening system, worthwhile review materials have been presented by Bai et al, 2014 [11] and Heshmati et al, 2015 [2]. All of these researches have collaborated to gather a large number of scattered information from all across the world and these data have been very useful to understand the conclusions being made and the present development in this area.

The main objective of the present paper is to review experimental bond testing procedures, surface preparation procedure, influence of loading and environmental conditions on the bond performance and bond strength evaluation approaches.

2. Bond testing

2.1 Bond testing methods

Three-point bending tests or four-point bending tests are performed to detect the adhesive shear stresses and peel stresses of the bonded joint when subjected to flexural loads. The load is indirectly applied to the FRP and these tests are generally used for steel members with I sections (Fig. 2). For other types of loading (Static tension, dynamic loading, etc.) adhesive joint test methods are performed. Adhesive joint tests can be categorized as overlap and shear joint tests, Peel tests and Pull – off tests [12].

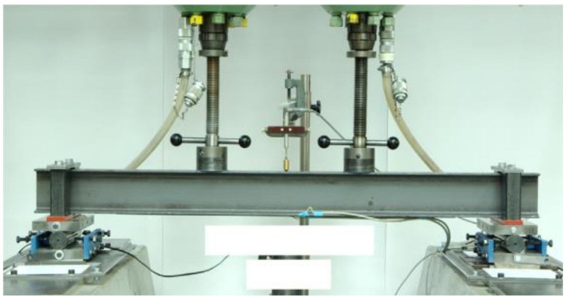
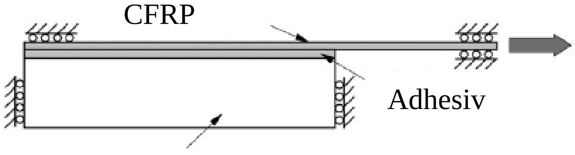
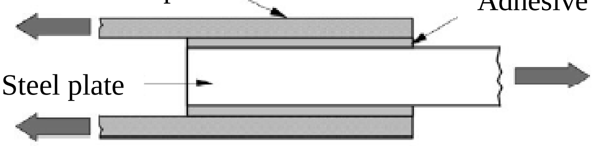


Fig. 2. Four-Point Bending Testing Arrangement [4]

Mostly used shear joint tests are Single – Lap joints (Fig. 3 a), Double – Lap joints (Fig. 3 b) and Double Strap joints (Fig. 4 a, b). Lap joint tests are carried out by applying tensile force directly to the FRP layer. Single lap shear joints are capable of detailed monitoring and inspection of the failure mechanism and in contrast, eccentricities may develop and bending of FRP layer and the rotation of the bonded region can be found. To eliminate the above situations by a symmetric arrangement, double lap shear joints are introduced. The applicability of these tests to CFRP sheets may be difficult as gripping is an issue. Stresses at the joints can be minimized by selecting a suitable adhesive type, modified shapes of joint ends and geometries of adhesive fillets [12]. Double strap joints are formed by direct application of loading to the steel element. This test is very popular in the literature and the concern of uncertainty in the de-bonding location can be overcome by using unequal bond lengths, mechanical clamping and transverse CFRP strengthening [3].



(a)



(b)

Fig. 3. (a) Single lap joint (b) Double lap joint [3]

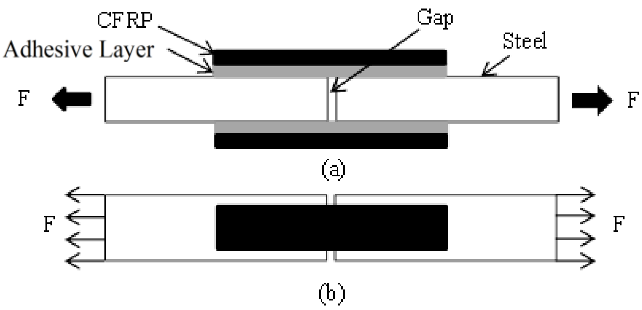


Fig. 4. Double Strap Joint (a) Side view (b) Plan view [13]

T-Peel tests are suitable for flexible adherends and can be used to evaluate the resistance of the adhesive system to the normal force peel loading. The suitability of the test results in generating design data is yet uncertain. To assess the adhesive bond strength of the adhesive, Pull – off and Butt joint tension tests (Fig. 5) can be used. Possible misalignments of the specimen or the applied load should be minimized for accurate results.

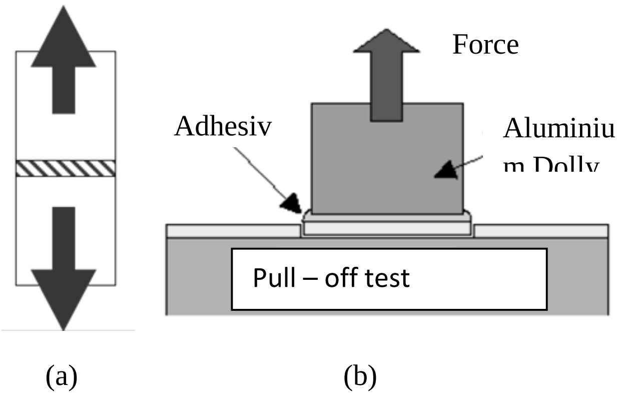


Fig. 5. (a) Butt – Joint test specimen and (b) Pull – off test specimen [12]

2.2 Surface preparation

Development of a proper surface preparation method is important as the maximum joint strength and the durability are dependent on the quality of the bond system [6,14]. Unsatisfactory surface treatment can end up with adhesive/adherend interface failure. Teng et al (2010) [15] have recently proposed that cohesion failure within the adhesive should be promoted so that the de-bonding failures can be addressed based on the adhesive properties. The requirement of a good surface preparation is to make the bonded surface free from contaminants, chemically active and resistant to environmental degradation.

Basic steps carried out in the passive treatment process of steel surfaces are summarized below and the prevailing standard guidelines are BS 7079 [16], ASTM D 2651 [17] and ASTM D 2093 [18].

i. Degreasing – removing contaminants like oil, grease and water.
   - Solvent cleaning (excess solvent application is effective as the contamination may deposit when the solvent evaporates [14]). One of the benefits of this method is the least effect on the surface properties of the steel substrate.
   - Brushing, ultrasonic degreasing and vapour degreasing have found to be efficient [14].

ii. Mechanical abrasion – roughening the surface and remove the weak, chemically inactive oxide layer
   - Grit blasting is found to be more effective. Sufficiently finer grit should be chosen (e.g: 0.25 mm [15]).
   - Other tools – sand papers, wire brushes, abrasive pads and wheels, needle guns etc.

iii. Removing fine abrasive dust before adhesion bonding – for grit blasted/ hand ground specimens.
   - By dry wipe or vacuum head
   - Solvent cleaning is not suggested because in case of insufficient application, effectiveness of the surface can be reduced.

3. Influence of loading

3.1 Static loading

Tensile and flexural loading tests are the basic testing methods for static loading. There are many research works conducted over the past decade with CFRP patched steel joints subjected to static loading. Being the most popular Civil Engineering application, these tests have been used to understand the basic behaviour of the CFRP bonded metallic members in detail. Some of the areas paid into attention were the failure modes of the bonded joints, function of material properties on the bond performance (Adhesive type, adhesive thickness, form of CFRP (laminates/sheets) and different CFRP elasticity modulus (LM, NM, UHM etc., Refer Table 1), effective bonding length, different CFRP configurations (1/3/5 number of CFRP layers) and bonding enhancement methods (tapered end joints, using mechanical clamps etc.)

3.2 Fatigue loading

Fatigue performance of CFRP strengthened steel members has shown excellent results by proving extended fatigue life and restrained crack growth. Moreover, fatigue strengthening has become a vital importance as steel bridges and other steel infrastructures are tend to confront increased traffic volumes, progressive aging and various environmental effects. Specifications and standards available are Eurocode category 3 [19] and AASHTO category E [20].

The research study conducted by Liu et al, 2010 [21] performing series of double strap joints has observed that failure modes of joints are not affected by fatigue loading. Moreover, it has been identified that bond strength reduction of NM CFRP patches is 20%, while there is only an insignificant effect on HM CFRP patched joints. Colombi et al, 2012 [22] carried out another series of double-strap joints using CFRP strips. The results have shown that the fatigue limit is approximately equal to the stress range of 75MPa and its dependence on the fatigue ratio is minimal. Wu et al, 2013 [23] proceeded with a similar procedure, yet using UHM CFRP plates. Obtained results were compared with the experimental results obtained by Liu et al and concluded that the fatigue behaviour is same for both UHM CFRP plates and HM CFRP sheets.

Bond performance of CFRP/Steel composites under fatigue loading can get affected more when they are met with severe environmental conditions. Studies done by Borrie et al, 2015/2016 [24,25] revealed that double lap joints exposed to marine environment at elevated temperatures for extended periods (1-6 months) can reduce bond strength of HM CFRP sheets by 20% and NM CFRP laminates by 28%. Effect of temperature is increased when it surpasses the Glass Transition period of the adhesive (Tg) and longer exposure periods combined with elevated temperatures can worsen the degradation. Silane pre-treatment, was recognized to be useful in reducing the degradation of the bond exposed to seawater and when the primary failure mode is a cohesion failure.

3.3 Impact loading

Another possible loading type which can be experienced by the bridges and other offshore structures are Impact loading. This loading behaviour is simulated in the laboratory by using different strain rates/loading rates on the CFRP strengthened steel joints. Double strap joints and Pull – off tests are being carried out in the experiments with the adoption of the drop mass technique. The obtained results are then compared with the results attained for quasi-static loading and the influence of impact loading on the bond behaviour is evaluated.

Experiments carried out by Al-Zubaidy et al [26,27] and Al – Mosawe et al [28,29] with quasi static loading rate of 3.34 x 10^{-4} m/s (quasi-static) and dynamic loading rates of 3.35 m/s, 4.43 m/s and 5 m/s can be summarized as below.

With NM CFRP sheets (CF 130):

Bond performance (Bond strength, failure modes) can be expressively different based on the mechanical properties of the adhesive type used. It has been realized that dynamic bond strength is increased when 3 CFRP overlays are used instead of 1 CFRP layer with Araldite 420 adhesive. However the number of CFRP layers did not affect the bond strength with the adhesive type MBrace saturant. Further, after the dynamic loading rate of 3.35 m/s, bond strength was slightly increased for Araldite 420 and for MBrace saturant, it decreased. This can be attributed to the elasto-plastic behaviour of Araldite 420 and elastic – brittle nature of MBrace saturant [26]. In addition, the effective bond length seemed to be independent of the loading rate and general trend of the strain distribution which is decreasing away from the joint is not changed with the number of CFRP sheets adopted at the joint.

With CFRP laminates:

The increment in the ultimate bond strength for both LM CFRP and NM CFRP was similar and it was comparatively less for UHM CFRP laminates. The reason can be understood as the low tensile strength and ultimate strain values of UHM CFRP plates. A similar trend of strain distribution for both LM and NM laminates could be observed. Ultimate strain values of UHM laminates are 2/3 times lower than for the LM/NM laminates and Increment of ultimate strain under dynamic loadings over static loading is about 15%.

4. Influence of environmental conditions

The effect of various environmental conditions on the adhesively bonded joint is an important factor which decides the durability of the FRP strengthening system. Lack of awareness on this matter is one of the reasons for restricted FRP applications in both severe/non severe environmental conditions. The key factors affecting the performance of the system are exposed temperature variations, moisture and humidity conditions, Ultraviolet radiation (UV) and marine environment. Most importantly, the combination of these two or more factors can be the most problematic situation above all.

4.1 Short Term Durability

Almost all the studies which have been studying the durability conditions have considered only the short term bond performance by conducting accelerated environmental tests. The compatibility of these tests with the actual environmental conditions is not yet confirmed and therefore proper validation is required by proceeding with adequate laboratory experiments.

Sub-zero temperatures and freeze thaw conditions can increase the brittleness and the hardness of the FRP matrix, inducing micro cracking and degrade the FRP/steel bonded joint. Al-Shawaf et al, 2006 [30] have shown that the effect of sub-zero temperatures on the bond strength is negligible. Yet the depending on the adhesive type and its mechanical properties, it may affect the bond behaviour differently. Freeze-thaw conditions cause to FRP de-bonding, matrix micro-cracking and the costs are greater with presence of salt as it accelerates degradation [6]. The effects of elevated temperature on the bond performance are more critical as it can lead to decrease the strength and stiffness of the resin and the adhesive. When the temperature is more or less equal to the Glass transition temperature of the resin/adhesive, they can soften and increase the viscoelastic response. This results to reduce the mechanical performance of the bonded joint and increase possibilities of moisture absorption [6]. On the other hand, increased temperature up to a certain level can be beneficial in post curing of the bonded joint.

Moisture ingress into the CFRP/steel bond can cause degradation of the adhesive as well as the adhesive/adherend interface. This can adversely affect the mechanical properties of the adhesive by plasticization or chemical/physical breakdown [11]. Durability study done by Dawood and Rizkalla, 2010 [31], considered a severe accelerated environmental condition with 5% NaCl solution, cyclic exposure condition of 1 week wet/1 week dry cycles at a temperature of 38^{0}C for an exposure period of 6 months. They had also considered 4 different double lap shear bond details; i) CFRP plates bonded to Steel with an adhesive (Type "A"), ii) Type "A" with a silane pre-treated steel plate (Type "B), iii) Type "A" with a Glass Fiber Reinforced Polymer (GFRP) layer embedded in between the steel and CFRP plates (Type "C") and iv) Combination of types "A" & "C" (Type "D"). Bond strength degradation of type A under the mentioned severe environmental condition was about 60% and type D had only 16% reduction of strength after 6 months (Fig. 6).

Another important point is the applied sustained load had only a negligible effect on the bond strength and the reasons for this observation may be due to the lesser value of load applied (35% of the initial bond strength) and the lesser exposure periods adopted. Studies have identified that influence of UV radiation on the bond strength is similar to that of associated temperature alone.

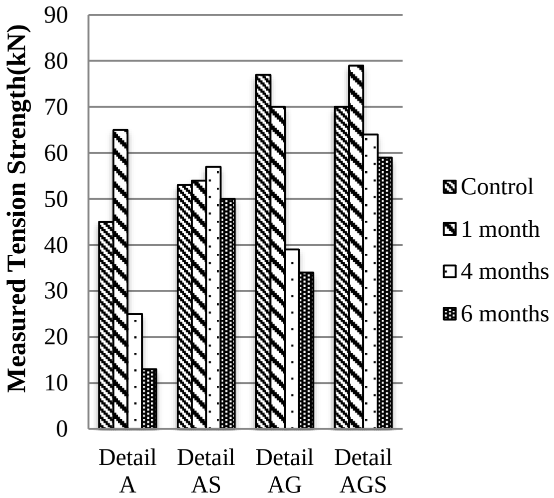


Fig. 6. Measured tension strength degradation of bond details (data from [31])

4.2 Long term durability

Very less number of studies are present, which evaluated the long term durability of the CFRP/steel joints. Nguyen et al, 2012 [32] tested series of double strap joints subjected to a sharp environmental exposure to simulated sea water (5% NaCl) at 20^{0}C and 50^{0}C for 1 year (Case 1). Two other different scenarios were compared with the former; 1.) A constant temperature of 50^{0}C and 90% RH and 2.) Cyclic temperature between 20^{0}C and 50^{0}C at 90 % RH. Schematic of strength and stiffness degradation of joints under 20^{0}C is shown in Fig.7. Heshmati et al, 2016 [13] carried out a long term durability investigation both numerically and experimentally to assess the effect of moisture on the bond performance of CFRP and GFRP considering different aging conditions (1 year in 20^{0}C distilled water, 20^{0}C and 5% NaCl, 45^{0}C and 95% RH, 45^{0}C distilled water and 45^{0}C & 5% NaCl). Observations conclude that the moisture ingression is dependent on the permeability of the adherend and reduction of elastic modulus of the adhesive is greater than that of the adhesive strength. Also, the influence of moisture on bond durability is a time dependant effect.

Deficient number of tests on the long term bond behaviour with respect to Civil Engineering applications should be highlighted and the experiments conducted for more than 12/18 months are encouraged. Validated finite element simulations can be more effective to understand this in more complex situations.

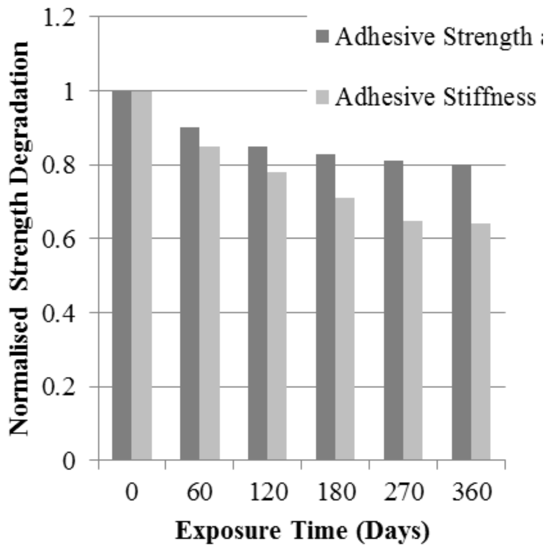
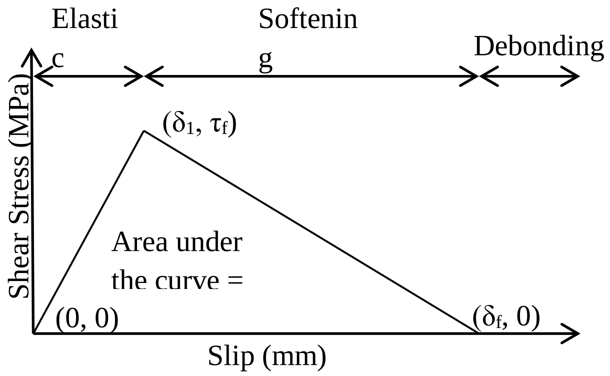


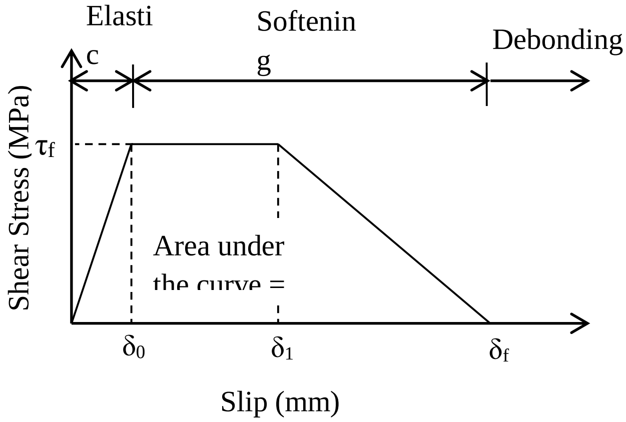
Fig. 7. Strength and stiffness degradation of the CFRP/Steel joints under 20^{0}C (data from [32])

5. Bond Strength Evaluation

There are several approaches to evaluate the bond strength of a CFRP strengthened steel system. The most common methods in use are 1) Strength/stress distribution approach, 2) Fracture mechanics based approach and 3) Bond-slip relationships. The first method calculates the bond stress distribution in the strengthened member based on the elastic material properties. The second method reflects the fatigue crack propagation and evaluates both analytical and finite element methods. Extensive research work is present, progressed in Aerospace Engineering. Bond – slip relationships can be used to predict the ultimate load values which can be withstood by the bonded joint as well as the effective bond lengths. These relationships are dependent on the properties of the adhesive (Elastic modulus, Tensile strength, Strain capacity) and interfacial fracture energy (Fig. 8; where δ_1 – initial bond slip, δ_f – final bond slip, τ_f – Peak shear stress and G_f – Interfacial fracture energy).



(a)



(b)

Fig. 8. Bilinear Bond – Slip Models (a) Proposed by Xia et al [33] (b) Proposed by Dehghani et al [34]

6. Conclusions

This paper has reviewed some of the influential research papers presented so far in order to understand the bond behaviour of CFRP strengthened steel joints. This summarizes the common bond testing procedures, surface preparation method and the effects of static loading, dynamic (fatigue and impact) loading and environmental conditions on the bond performance. Future research works are needed to validate accelerated environmental tests so that the actual environmental conditions are simulated. The bond behaviour of the strengthened members subjected to dynamic loading (fatigue and impact) should be thoroughly investigated especially under severe exposure conditions. Long term behaviour of the CFRP/steel bonded joint under different loading and the environmental conditions should be implemented. Further, the factors affecting for the bond-slip models should be studied in order to make the relationship more reliable and useful.

Acknowledgement

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