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Numerical and analytical investigation on workings of mechanical anchorage of CFRP sheets

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ABSTRACT: The field of retrofitting unreinforced masonry (URM) walls by means of modern composite materials has been widely studied during the last two decades. An extensive experimental campaign on the retrofitting of masonry walls via two types of carbon fiber reinforced polymer (CFRP) sheets (C-sheets 240-200 g/m^2 and C-sheets 240-200 g/m^2) has been carried out at the University of Applied Sciences (UAS) Fribourg. These experiments have shown that CFRP sheets can be efficiently employed for the seismic upgrading of URM walls. Moreover, it has been found that effective anchorage of CFRP sheets can be achieved when eccentric loading of the mechanical anchorage is avoided and a smooth bonding surface is guaranteed. Additionally, an analytical study and an approximate numerical investigation, both based on knowledge from bonded joints between CFRP plates and steel, were conducted in order to gain a deeper insight in the bonding behavior including the effective bond length, an important parameter for the design of a mechanical anchorage. This paper focuses on the results of this analytical study and of these additional approximate numerical analyses and provides a comparison to the experimentally obtained results. It is found that the failure load obtained via numerical analyses for C-sheets 240-200 g/m^2 is very close to the maximum failure load, derived from the experiments. However, for the heavier C-sheets 240-400 g/m^2, the experimental results of bonded joints between CFRP sheets and steel did yield failure loads that are, in general, higher than analytical equations for bonding and, hence, the numerical simulation would suggest, which indicates a topic calling for more extensive investigation.

1 INTRODUCTION

In Europe, masonry buildings constitute a particularly large portion of existing building patrimony. Issues pertaining to the condition assessment of these structures are well documented in the literature. The structural walls of these buildings have been principally designed to resist gravity loads. However, the horizontal loads induced by earthquake loading result in the development of in-plane and out-of-plane forces (Paulay and Priestley, 1992).

In Switzerland, the need for updating the design standards came with the Swiss norm series of 2003, where the required level of safety was adjusted to Eurocode 8 and the seismic risk zones were redefined relying on the most recent seismologic knowledge (Wenk, 2004). As a result, a large number of buildings in Switzerland constructed prior to 2003 are incapable of withstanding the updated design earthquake. Therefore, strengthening and retrofitting methodologies are deemed crucial.

Retrofitting existing masonry buildings by means of fiber reinforced polymer (FRP) is at this point a frequently implemented strengthening solution. The FRP solution is attractive, since retrofitting can be performed quickly and without deep interventions in the load carrying structure of the building as would be necessary for example, when masonry walls are substituted by reinforced concrete (RC)-walls. Various types incorporating different materials, forms, orientations (uni- or bidirectional) of FRP are available.

At the University of Applied Sciences (UAS) Fribourg, the retrofitting of masonry walls has developed into a major research focus since 2007. Theoretical studies and experimental campaigns at UAS Fribourg have mainly focused on the use of high performance fibers (carbon, glass and aramid) in different applications and are presented in Bischof and Suter (2014), in Bischof, Suter, Chatzi, and Lestuzzi (2014), as well as in Suter, Broye, and Grisanti (2010). Within an extended research campaign labeled AGP 21159, "Seismic retrofitting of masonry walls", retrofitted URM walls and mechanical anchorages of CFRP sheets were subjected to a series of tests. In Bischof et al. (2014), a systematic analysis based on the outcomes of the extensive experimental campaign with CFRP sheets is presented and guidelines on the practical implementation of such retrofitting solutions are provided.

In the experimental study on mechanical anchorages of CFRP sheets, it has been shown that the bonded CFRP-to-steel joints govern the ultimate bearing capacity of the mechanical anchorage by means of aluminum or steel profiles. So far, however, very little testing of the bonding behavior of CFRP sheets on metallic adherends has been carried out in the scientific community. In this article, an analytical study and an approximate numerical investigation, both based on knowledge from bonded joints between CFRP plates and steel, were conducted in order to gain a deeper insight in the bonding behavior including the effective bond length, an important parameter for the design of a mechanical anchorage.

Firstly, a short overview of the test results of the experimental series AT-H is given. For Series AT-H, double shear tests were performed in order to study the bonding mechanism of CFRP sheets on steel. Secondly and mainly, the results of the analytical and numerical study is presented in detail and compared to the experimental results.

2 EXPERIMENTAL STUDY

In Series AT-H, double shear tests with CFRP sheets bonded to steel profiles were conducted, as shown in Figure 1. The double shear tests aimed to give an idea of the applicable load on CFRP sheet-steel-joints.

Two different CFRP sheets were used in the experiments of Series AT-H: the S&P C-Sheet 240 200 g/m^2 and the S&P C-Sheet 240 400 g/m^2. For the mechanical anchorage in Series AT-H, steel profiles were used as adherends. The material properties of the CFRP sheets and the adhesive used in the experiments are given in Table 1.

Eight tests, four with C-sheet 200 g/m^2 and four with C-sheet 400 g/m^2 were performed. The maximum load with C-sheet 200 g/m^2 was reached in test AT-H2 with 71 kN, corresponding to a fiber tensile stress of 2022 N/mm^2 whereas the maximum load with C-sheet 400 g/m^2 was reached in test AT-H10 with 138kN, corresponding to 1972 N/mm^2. For further details of the experimental series AT-H, see Bischof et al. (2014).

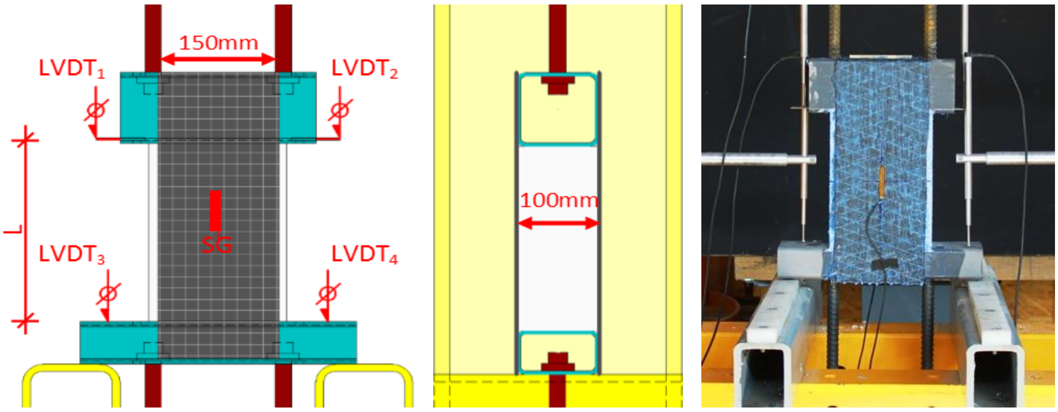

Figure 1: (a,b) Model with instrumentation of specimen in Series AT-H in view and sectional drawing; and (c) specimen of Series AT-H.

Table 1: Properties of CFRP sheets (linear-elastic range) and adhesive given by manufacturer

CFRP sheets		S&P C-Sheet 240 200 g/m^2	S&P C-Sheet 240 400 g/m^2
	Young's modulus E [N/mm^2]	240000	240000
	Theoretical tensile strength per fiber f_u [N/mm^2]	3800	3800
	Theoretical design cross section 1 m width [mm^2/m]	117	234
Adhesive		S&P Resicem	
	Young's modulus E at +20°C. [N/mm^2]	4820	
	Tensile strength after 14 days f_u [N/mm^2]	22	
	Pull off strength on steel [N/mm^2]	> 10.6	

3 ANALYTICAL STUDY

Various failure modes of FRP bonded to steel are possible when the FRP is subjected to tensile loading, as summarized by Zhao and Zhang (2007) (see Figure 2).

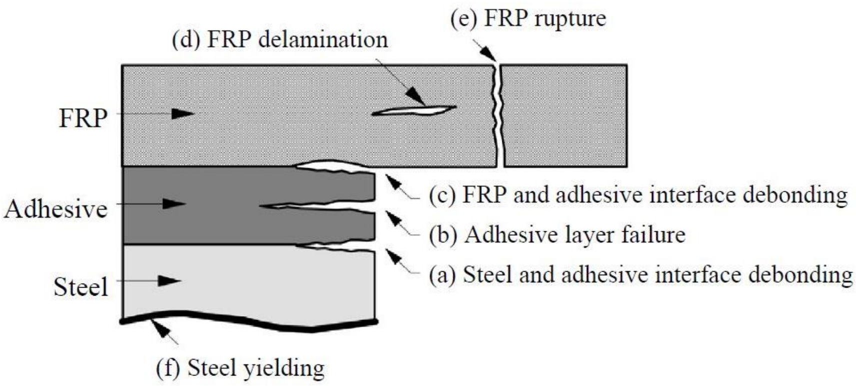

Figure 2: Possible failure modes of FRP bonded to steel (Zhao and Zhang, 2007).

Fernando (2010) states that the failure mode "cohesive failure in the adhesive is the preferred mode of debonding failure at CFRP-to-steel interfaces" for CFRP plates. He found in so-called "near-end supported single-shear pull-off tests" that a bi-linear bond-slip model fits the bonding behavior of linear adhesives best. Xia and Teng (2005) establish an equation to determine the effective bond length for CFRP plates bonded to steel adherends by means of linear adhesives.

They further state that the values for the slip δ_1 at peak shear stress are generally very small compared to the values of the slip at bond failure δ_f. Therefore, they simplify the bilinear bond-slip model assuming a rigid ascending branch followed by a linearly descending branch. The effective bond length l_e can then be obtained by:

$$l_e = \frac{\pi}{2\sqrt{\frac{\tau_f}{E_p t_p \delta_f}}} \tag{1}$$

where τ_f is the maximum local bond strength and can be calculated through the assumption $\tau_f = 0.9 f_{t,a}$ (according to Fernando, 2010), with $f_{t,a}$ representing the tensile strength of the adhesive. E_p and t_p representing Young's modulus and the thickness of the CFRP plate, respectively, whereas δ_f represents the ultimate slip. The ultimate load P_{ult} of CFRP plates-to-steel bonded joints with a bond length greater than the effective bond length can be calculated as:

$$P_{\text{ult}} = b_p \sqrt{2 G_f E_p t_p} \tag{2}$$

where G_f is the failure interfacial fracture energy of the steel-FRP joint. The interfacial fracture energy can be obtained with a best-fit equation proposed by Fernando (2010):

$$G_f = 628 t_a^{0.5} R^2 \tag{3}$$

Here, t_a represents the thickness and R the tensile strain energy of the adhesive. R may be assumed to be equal to the area under the uni-axial tensile stress-strain curve with a linear-elastic material. Therefore, Fernando (2010) takes the strain energy to be $R = f_{t,a}^2 / E_a$, with E_a being the Young's modulus of the adhesive. Hence, the slip at failure δ_f for linear adhesives can easily be derived by using the form of the bilinear bond-slip model: $\delta_f = 2G_f/\tau_f$.

The slip δ_1 at peak shear stress can be found with a best-fit equation defined by Fernando (2010):

$$\delta_1 = 0.3 \left(\frac{t_a}{G_a}\right)^{0.65} f_{t,a} \tag{4}$$

It is assumed that Equations (1)–(4) hold not only for CFRP plates, but also for CFRP sheets. When applying these equations to the used C-sheet 200 g/m^2, the used adhesive and a total approximate adhesive thickness of 0.5 mm, a theoretical effective bond length of l_e = 20 mm and, with two bonded surfaces with a 150 mm wide sheet, an ultimate load of P_{ult} = 75.5 kN corresponding to σ_{ult} = 2152 N/mm^2 are obtained. When applying these equations to the used C-sheet 400 g/m^2, the used adhesive and a total approximate adhesive thickness of 0.5 mm, a theoretical effective bond length of l_e = 28 mm and, with two bonded surfaces with a 150 mm wide sheet, an ultimate load of P_{ult} = 106.8 kN corresponding to σ_{ult} = 1522 N/mm^2 are obtained.

4 APPROXIMATE NUMERICAL INVESTIGATION

4.1 Basic Numerical Model and Boundary Conditions

The numerical simulations were performed using ABAQUS software (2010). The numerical investigation focused on the simple configuration tested in Series AT-H (see section 2). For the numerical simulation, the 0.117 mm thick C-sheet 200 g/m^2 was assumed to be bonded only on one side of a rectangular hollow section (RHS) steel profile. Considering the curvature of the steel profile, the bonded length allowing shear transfer corresponds to 40 mm. The adhesive thickness is measured to be approximately 0.5 mm. The basic model is shown in Figure 3.

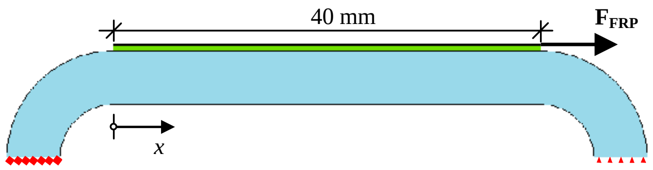

Figure 3. Basic numerical model with steel (light blue), adhesive (green), and CFRP (black).

4.2 Material Modeling

Three materials were considered for the numerical analysis of FRP-to-steel bonded joints, namely FRP, steel, and adhesive.

The FRP is defined as a linear elastic isotropic material, in accordance to Obaidat et al. (2010). The used FRP sheets essentially are unidirectional and, hence, constitute an orthotropic material. However, as loading only occurs in one direction, the Young's modulus in the primary direction is decisive for the results. Therefore, the linear elastic isotropic material is considered suitable. The Young's modulus in the principal direction is 240000 N/mm^2. The Poisson's ratio in all directions is assumed to be $\nu = 0.3$ (as e.g., in Obaidat et al., 2010, or Bocciarelli et al., 2009).

For steel, a linear-elastic perfect-plastic and isotropic behavior is assumed. The simulation was carried out for a part of rectangular steel profiles of quality S355. Strain-hardening is neglected. Since the simulations are aimed at studying the bonding interface, the plastic behavior of the steel profile is of secondary importance.

The adhesive is modeled using cohesive elements with uncoupled elastic behavior. The adhesive thickness was measured as approximately $t_a = 0.5$ mm in all tests with C-sheet 200 g/m^2. The important material properties used for numerical modeling of the adhesive are:

- Tensile strength $f_{t,a} = 22.0$ N/mm^2
- Peak bond stress $\tau_f = 0.9 f_{t,a} = 19.8$ N/mm^2
- Mode I stiffness $K_{nn} = E_a/t_a = 9640$ N/mm^3, being the initial slope of the bond-separation model
- Mode II stiffness $K_{ss} = K_{tt} = 3(G_a/t_a)^{0.65} = 625$ N/mm^3, being the initial slope of the bond-slip model
- Fracture energy $G_{II,F} = 1.13$ N/mm

It is assumed that the adhesive's behavior is linear elastic and, hence, that a bilinear bond-slip model is suitable for modeling the bonding behavior. The bond-slip model used for the numerical simulations and based on the material properties defined above is shown in Figure 4. It is given by the peak shear stress τ_f and the corresponding slip δ_1, as well as the slip at failure δ_f.

4.3 Results of Numerical Simulations

Figure 5 shows the bond shear stress in function of the applied load for every numerical element, distributed over the bonded length. Resulting from the bilinear bond-slip model, the curves in Figure 6, representing bond shear stress over the length at different stages of applied load, show a hyperbolic behavior until the peak shear stress is reached. When in the softening region, they show a harmonic behavior instead.

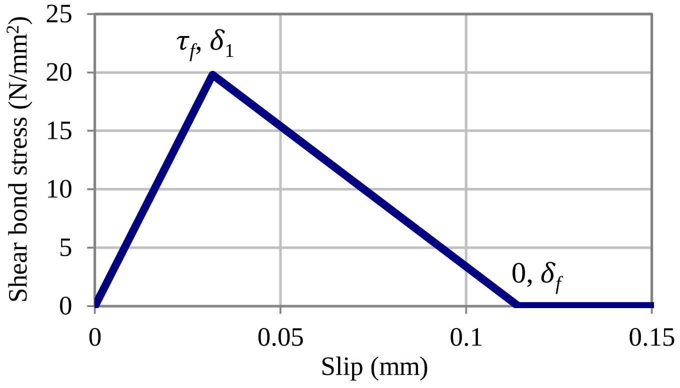

Figure 4. Shear bond-slip model for bonded CFRP-steel joint.

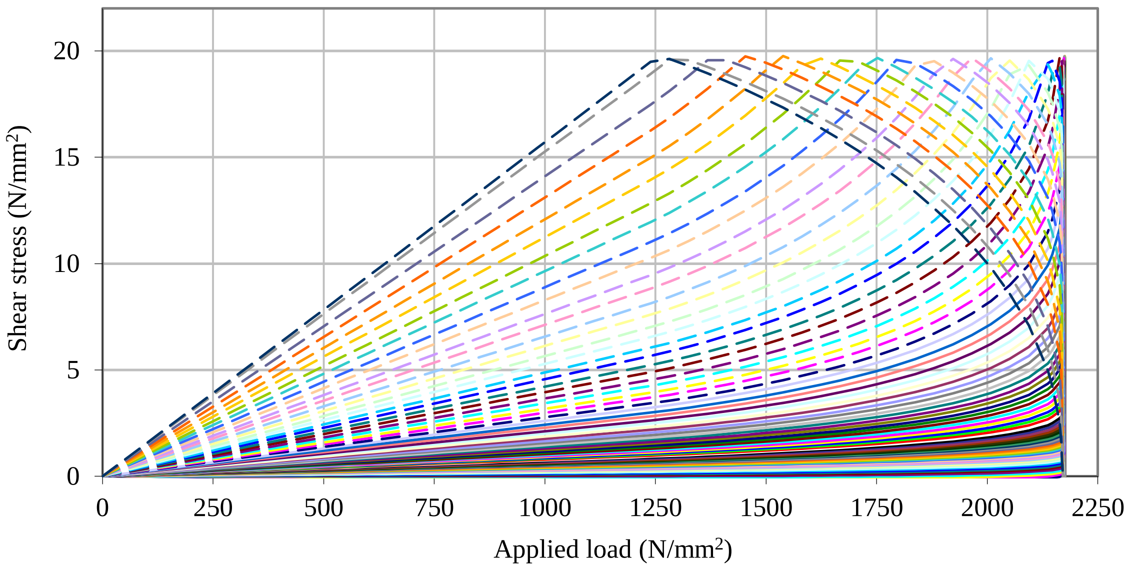

Figure 5. Bond shear stress for every numerical element along bonding interface in function of applied load.

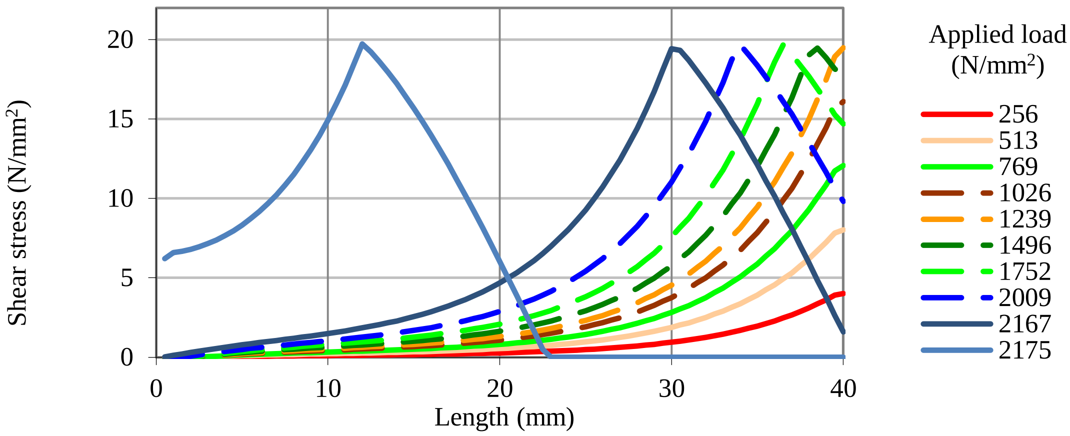

Figure 6. Bond shear stress in function of bond length. Bonding interface is loaded in direction from right to left hand side.

It can be seen that up to 2000 N/mm^2, only the first 3–5 mm of the bonding interface fails. At this point, local failure due to stress concentrations occurs to reduced extents. After debonding initiates, the shear stress transfer propagates and the ultimate bonding capacity is reached very quickly. The curve for an applied load of 2167 N/mm^2 still indicates an intact shear stress transfer, whereas the curve for the maximum applied load of 2175 N/mm^2 depicts a mostly debonded state at failure. Hence, the comparison between the analytical results based on empirical models for CFRP plates and the numerical simulations bring about very similar results. This is to be expected given the fact that the ultimate load mainly depends on the interfacial fracture energy. The fracture energy was considered the same in both, analytical and numerical study. However, the curve for an applied load of 2167 N/mm^2 seems to show that the effective bond length is higher than the analytically calculated 20 mm, because the shear stress did not reach to zero at 20 mm but at approximately 40 mm. Due to the lack of a valid bond-slip model for CFRP sheet-to-metal-joints, further research including experimental studies and possibly fracture mechanics is required.

5 CONCLUSION

The maximum load obtained by the experimental study is 138 kN for C-sheets 240-400 g/m^2. If bond shear stress is assumed to be uniformly distributed over the whole bonded surface, this maximum load corresponds to a bond shear stress of 11.2 N/mm^2. Considering the actual shear bond transfer over the effective bond length described by a hyperbolic behavior up to the maximum bond shear stress and a subsequent harmonic behavior, when assuming a bilinear bond-slip-model (which holds for linear adhesives, according to Fernando (2010), the maximum bond shear stress has to be significantly higher than the minimum value (10.6 N/mm^2) given by the manufacturer for the adhesive S&P Resicem.

The failure load obtained by the numerical simulations for C-sheets 200 g/m^2 is very close to the maximum load obtained by the experimental study on bonded CFRP sheet-to-metal joints in Series AT-H. However, for the heavier C-sheets 240-400 g/m^2, the experimental results of Series AT-H did yield failure loads that are, in general, higher than analytical equations would suggest. Nevertheless, in order to study the bond-slip behavior of bonded CFRP sheets-to-steel joints in more detail and to provide adjusted analytical models for bonded CFRP sheets, a more intensive instrumentation for experiments adjusted to the short effective length is required.

From both the experimental and the numerical study, it can be concluded that the effective bond length of CFRP sheets on metallic adherends is rather short. Given the rather high maximum applied fiber tensile stresses reached in Series AT-H, the bonded length of 40 mm for the aluminum profiles can be considered as sufficiently long for both CFRP sheet 240-200 g/m^2 and CFRP sheet 240-400 g/m^2.

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