Carbon-fibre composites for strengthening steel structures

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Abstract

The use of composite materials for strengthening and repair of steel structures has attracted a great deal of attention during the last years. In this paper, the research work conducted at Chalmers University of technology during the last five years in this field is reviewed. The results from various types of tests are summarized and discussed. Aspects related to stress analysis of adhesive joints, joint modification and failure modes in steel elements strengthened with bonded CFRP-laminates are discussed. Research needs within the studied problems are also highlighted.

Keywords: Composites, strengthening, adhesive joint, failure, tapering, fillets

Notations

G_{IC}	Critical energy release rate (mode I)
α	Peeling stress coefficient
β	Shear stress coefficient
κ	Stiffness ratio
σ	Interfacial peeling (normal) stress
σ_1	Principal stress
σ_{ult}	Ultimate peeling strength
$\overline{\sigma}$	Principal stress in lap-joint
τ	Interfacial shear stress
τ_{ult}	Ultimate shear strength

1. Introduction

Bonding composite materials to strengthen structural elements has attracted a great deal of attention in recent years and a large number of studies have been devoted to this area. The outstanding properties of composite materials such as high strength, high elastic modulus, light weight and good durability have made them a suitable alternative for steel plates in strengthening work. In addition, the adhesive bonding technique offers several advantages such as ease of application and improved fatigue behaviour. This has made bonding a good alternative for conventional jointing techniques such as welding and bolting.

Composite laminates used for strengthening purposes usually consist of unidirectional fibres embedded in an adhesive matrix or so-called unidirectional laminates. One inherent feature of this structure is the clear anisotropy in the properties of the laminate in terms of both stiffness and strength. In the longitudinal direction, the stiffness and the strength are very high, whereas the transverse (i.e. perpendicular to the fibre direction) stiffness and shear strengths are much weaker. The through-thickness modulus of unidirectional laminates is only two or three times that of the matrix and the strength is of the same order as that of the matrix or, in some cases, even less [1]. On the other hand, the strain capacity of structural adhesives is very limited in tension, as compared with shear [2].

Compared with concrete structures, in which failure mostly takes place in the concrete cover due to the poor behaviour of concrete in tension, the state and modes of failure are more complex in strengthened steel members. The strength of steel is usually superior to that of conventional adhesives used in strengthening applications. This, in addition to the low strength of unidirectional composite laminates, result in a variety of possible failure modes in steel members strengthened with bonded CFRP-laminates. Failure of the adhesive, through-thickness failure of composite laminate, i.e. delamination, or failure along the interfaces, i.e. debonding are the possible modes needed to be considered in the design of CFRP-strengthened steel members.

Owing to this variety in possible failure modes and the lack of knowledge regarding the behaviour of composite materials in adhesively bonded joints, more research is needed before a wide implementation of the strengthening techniques is feasible in practice.

The following paper summarizes the research work conducted within the frame of this subject at Chalmers University of Technology during the last five years. First, the experimental work conducted in view of the problem is reviewed along with the main findings from these tests. Test results were in most cases supplemented with finite element analysis to gain a more detailed understanding of the behaviour of the tested specimens. The experience from these analyses is also summarized. Aspects related to the design of strengthening schedules with adhesively bonded composite laminates are also discussed and the needs for further research and development are highlighted.

2. Evaluation by testing

The mechanical properties of both adhesives and carbon-fibre composites were evaluated using standard tension tests. For the CFRP-composites, the tests were conducted on several types of laminates with different stiffness and strength classes. The tensile strength, E-modulus and Poisson’s ratio were obtained in two orthogonal directions, parallel and perpendicular to the direction of the fibres in the laminate. Three different types of adhesives were also tested to evaluate their stress-strain behaviour at different temperatures and different curing times. In addition to material testing, the fracture energy of the composite material and that of the adhesives were also evaluated experimentally using standard ENF (End Notched Flexure) and DCB-tests (Double Cantilever Beam. These tests also provided valuable information on the strength of the two materials in pure shear and tension modes.

In order to investigate the bond strength of adhesively bonded steel-CFRP-laminates, three-point bending tests were conducted on small-scale specimens with different material combinations. These tests proved to be a simple and effective method for establishing the bond strength and examining the effect of related issues such as surface preparation.

An important problem, specifically related to steel elements strengthened with bonded CFRP-laminates is the effect of yielding (local or global) on the behaviour and strength of these elements. Test specimens, specially designed to study these effects were used. In these tests, different combinations of adhesive-CFRP-laminates were used to examine how the mechanical properties of these materials affect the behaviour and strength of the composite elements and the type of fracture modes that can be expected in these elements. Finally, the behaviour and strength of steel beams strengthened with bonded composite laminates were studies through a series of static test. Five HEA180 beams were tested here. The beams were strengthened with different combinations of adhesive-CFRP-laminates and loaded in four-point bending. Extensive measurement programme was carried out in these tests to monitor the strains and deformation at different sections along the beams.

3. Analytical and numerical modelling of adhesive joints

Stress analysis is an important step followed by engineers in all structural design practices. The main goal of analysis is to provide the designer with reasonably accurate information on load effects (for example stress or strain) in the joint due to a specified loading and service condition. This information will enable the designer to predict the strength and service life of the joint. Accurate determination of the stress distribution in adhesively bonded joints is one of the most challenging structural analysis problems. Aspects such as stress concentration due to geometric discontinuities cause uncertainty in predicting the load-carrying capacity of adhesive joints.

Stress analysis techniques can generally be classified into two main categories; analytical analysis based on some simplifications and assumptions, and numerical analysis mostly using FE method. Analytical analysis is usually conducted in order to obtain fast and simple close-form solution with reasonable accuracy, while numerical analysis is mostly conducted to get a more detailed and accurate understanding of the problem analysed. An important issue in FE-analysis is that the type and density of the mesh should be chosen so that accurate results can be obtained.

Both methods have their own advantages and shortcomings. The FE analysis usually provides more detailed results while it is more difficult and time consuming in comparison to analytical analysis. Furthermore, using FE analysis, it is possible to model complex geometries of adhesive joint which otherwise are very difficult to treat in closed form solutions. Adhesive joints with tapered laminate and joints with spew fillets are only two examples of such cases. Using FE analysis it is also possible to study the effects of material nonlinearities, whereas closed-form solutions are mostly based on elastic material properties. On the other hand, a major drawback of the FE in analysis of adhesive joints is presence of bi-material wedge singularity at the ends of interfaces which makes it difficult to evaluate the stresses in vicinity of these points. Analytical solutions are generally based on the assumption of uniform distribution of stresses through the thickness of the adhesive layer. While this assumption might be adopted in thin adhesive joints, its application to the relatively thick adhesive joints that are often found in strengthening applications (usually 2-3 mm) becomes questionable.

In present studies FE-models built of either 3D-brick elements or 2D-shell elements have been used. The FE analyses have been carried out with steel and epoxies modelled as both linear and non-linear materials, while the CFRP laminates have been modelled as a linear material. However, the effect of the orthotropic behaviour of the CFRP laminates has been studied. For the analyses of the interfacial stresses the region near the end of the bond line was modelled with a dense mesh, where the element size was in the order of 0.25 x 0.25 mm. This results in 8 elements through the thickness of the adhesive layer. Full interactions between the materials have been assumed at the interfaces.

A widely used closed-form solution for the problem of interfacial stresses in beams strengthened with bonded laminates is the one developed by Smith et al. [3]. This solution was further developed by Deng et al. [4] and Schnerch [5] to include temperature effects (i.e. the effect of the difference in the coefficients of thermal expansion between the steel and CFRP) and the effect of prestressing the CFRP-laminate. Another similar closed-form solution has been proposed by Stratford et al. [6].

4. Upgrading the moment capacity of beams in bending

Fig. 1 shows the load-strain curves that were obtained from the beam tests. The strains here refer to the measures strains on the outermost fibres of the beam lower flange at midspan.

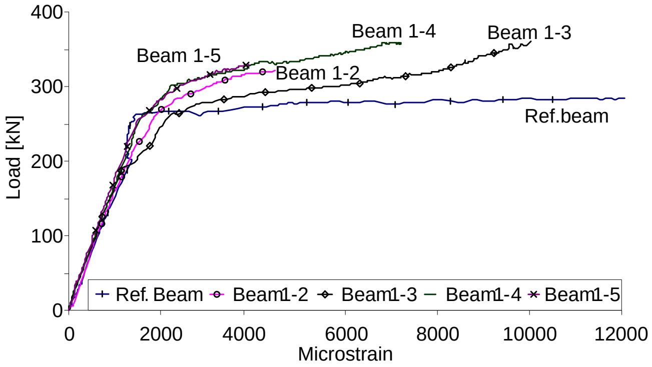


Fig. 1. Load vs. strain in beam lower flange as measured for the beams tested in laboratory.

The increase in bending stiffness achieved by bonding the laminates is very limited for all strengthened beams. This is of course expected as the amount of added reinforcement was limited from 4% up to 7.5% of the area of the steel section.

The maximum increase in moment capacity was obtained for beams 1-4 and 1-3 (about 18%). These two beams were also the ones which showed the highest ductility. In both beams high-strength laminates with high ultimate strain at failure were used. The material properties of the CFRP laminates and epoxies are given in Table 1. The material properties of the epoxies and the CFRP laminates were obtained from laboratory tests (four specimens of each kind, which not is enough to provide a statistical confidence level).

Table 1: Material properties

Test specimen	CFRP		Epoxy		A^2[mm^2]
	f_t^1 [MPa]	E [GPa]	f_t^1 [MPa]	E [GPa]	
Beam Ref	-	-	-	-	-
Beam 1-2	3100	165	30	7	291
Beam 1-3	3300	200	25	7	227
Beam 1-4	3300	200	25	7	340
Beam 1-5	1500	330	25	4,5	180

[1] Ultimate strength in tension. [2] Total area of CFRP material.

All beams, but one failed by rupture of the laminate near beam midspan. Beam 1-2, however, failed prematurely due to debonding. Investigation of the failure surface shows that the adhesion between the steel flange and the primer was poor and failure took place along this interface. A more detailed description of the beam tests can be found in Linghoff et al. [7].

A study of the distribution of the normal (bending) stresses over the height of the steel section reveals the behaviour of the strengthened beam in the plastic regime. When yielding of the steel section starts, the level of the neutral axis moves towards the tension flange to accommodate for the high tensile force in the CFRP laminates which are bonded to the tension flange. The stress distribution over the height of the steel section for different load levels is plotted in Fig. 2 for one of the strengthened beam. Similar results were obtained from the strain measurements. When yielding progresses through the compressed (upper) part of the cross-section, the part of the cross-section in tension is reduced and higher tensile forces are transferred to the CFRP-laminates (in order to maintain equilibrium over the strengthened section).

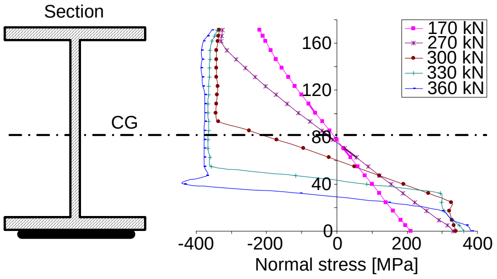


Fig. 2. Normal stress distribution over the height of the strengthened steel section at different load levels. Results obtained from FEM analysis.

For a double-symmetrical steel girder, which has to be strengthened in bending, this may limit the level of strengthening that can be achieved by bonding CFRP to the tension side only. To increase the moment capacity further, the compression side of the cross-section also needs to be strengthened. Thus, the maximum increase in moment capacity that can be achieved for a steel beam with a double symmetric cross-section is about 20%. For such an application that relies on full yielding of the steel beam cross-section, laminates with high tensile strength (ultimate strain at failure) are more appropriate than high-modulus laminates. Of course, in order to reach this strengthening effect, local and global instability problems should be avoided and the strengthening scheme should be designed so as to avoid premature failure due to debonding, for example.

5. Interfacial stresses

In composite elements, such as beams with adhesively bonded CFRP-laminates, there exist interfacial stresses along the bond line as a result of the composite action between the beam and the bonded laminate. These stresses reach their maximum values near the ends of the bond line and can result in failure of the strengthening scheme. In steel beams undergoing plastic deformation, high interfacial shear stresses also exist at the frontiers of the plastic regions. These stresses might actually exceed the stress concentration at the ends of the joint and in some cases govern the failure load of the strengthened composite member.

Efforts were made in most experimental work in this study to capture these interfacial stresses by means of strain measurements. Owing to the fact that the stress concentration at the end of the joint is very high, very small strain gauges placed with close distance apart had to be used. For this purpose, “spiders” with ten 0,7 mm long strain gauges were used. The distance between the strain gauges was 1 mm, see Linghoff et al. [7].

Fig. 3 shows an example of the results obtained from a beam test. The shear stresses in this figure were derived from the measured normal strains on the top surface of the laminate and are compared to the values obtained from the analytical solution [3]. It is obvious that the measured and the theoretical distribution differ near the end of the joint (the first 2 cm) where the highest stress concentration appears. The same deviation was observed in all beam tests.

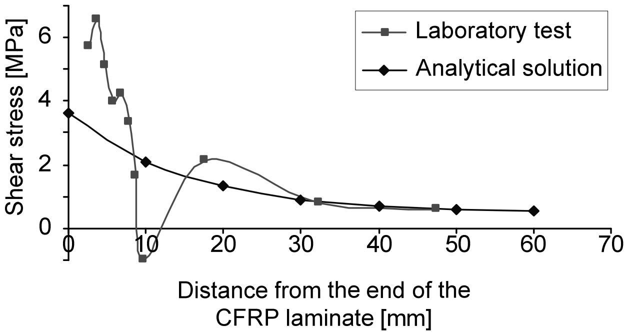


Fig. 3. Comparison of the interfacial shear stress distribution at the end of the bond line. Values obtained from the laboratory test (derived from strain measurements) and from the analytical solution [3].

The results from the FE-analyses of the tested beams show that the distribution of the interfacial shear and peeling stresses over the width of the bond line was not constant, which otherwise is the assumption adopted in all analytical solutions. This difference in stress distribution is seen over the whole force transfer length along the bond line, see Fig. 4. Also the peeling stress shows the same trend. This variation of interfacial stresses over the width of the bond line is caused by a combination of flange curling and shear lag effects in the wide flange of the I-section beam.

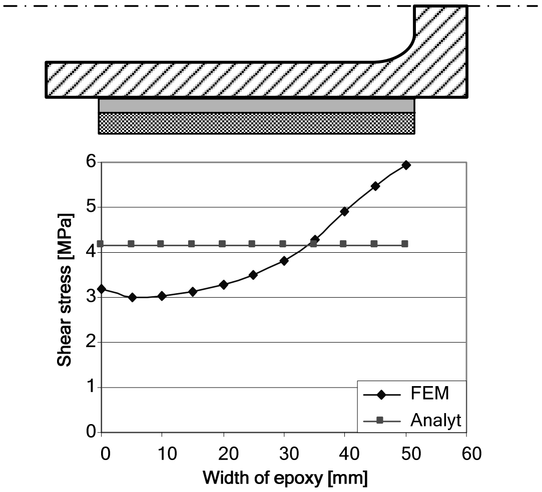
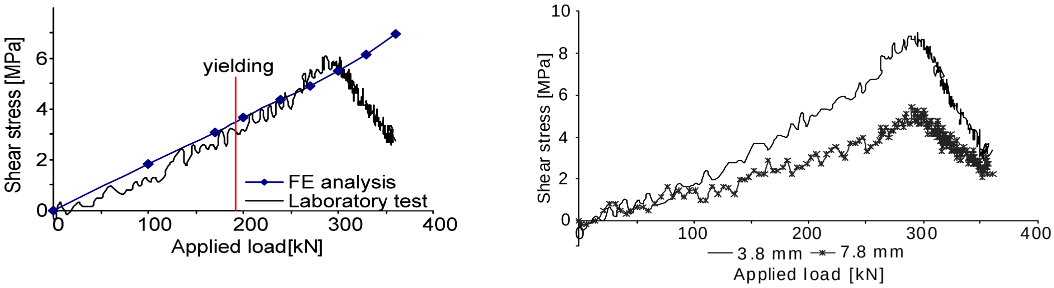


Fig. 4. the distribution of shear stresses over the width of the bond line, from FE-analysis and analytical solution.

Existing low-order analytical solutions for the prediction of interfacial shear and peeling stresses in adhesive joints assume in general linear elastic behaviour for all materials involved. Fig. 5.a shows the variation of shear stress near the end of the CFRP-laminate as a function of the load applied on the beam. A comparison is made here between the values derived from the test and those obtained from the FE-analysis. The results show good agreement even after the onset of yielding in the steel beam. This yielding takes place near beam midspan at an applied load of about 200 kN. After extensive plastic deformation, there is a drop in the value of shear stress at the end of the CFRP-laminate, which could not be "captured" by the FE-model. Fig. 5.b shows the variation of shear stress at two distinct points 3.8 and 7.8 mm from the end of the CFRP-laminate displaying the same trend. This indicated that the observed drop in shear stress was likely caused by a global phenomenon rather than by local effects at the end of the bond line (like nonlinear behaviour of the adhesive, for example). The reason for this decrease in shear stress near the end of the bond line is not yet been fully understood. Similar behaviour was also reported in [8].



a) b)

Fig. 5. Interfacial shear stress near the end of the CFRP-laminate as a function of applied load; a) comparison between FE-analysis and analytical solution. b) Derived from strain measurements, 3.8 and 7.8 mm from the end of the CFRP-laminate.

In steel members strengthened with bonded CFRP-laminates, yielding of the steel will also generate high interfacial stresses in the adhesive layer near the frontiers of the yielding area. These stresses are caused by the high difference in deformation (strains) between the yielding steel and the stiff CFRP-laminate and can in some cases exceed the stresses experienced at the ends of the joints. The presence of interfacial stresses generated by yielding was evident in the beam tests, both from the strain measurements and the clear pattern of cracking in the adhesive over the yielding region (the adhesive layer contained cracks that were oriented with 45 degrees over the entire yielding zone). Nevertheless, none of beams actually failed due to this load effect. In order to investigate the effect of progressive yielding in steel elements strengthened with bonded CFRP-laminates, new test specimens were developed and tested. Different CFRP-adhesive combinations were investigated to study the effect of material and geometrical properties on the behaviour and strength of these elements.

Fig. 6 shows the distribution of shear stresses along the bond line, obtained from the FE-analysis of on of the tested specimens at three different stages of loading. Yielding of the steel plate in the middle of the specimen took place at a load of 120 kN. Before yielding, very low shear stresses are present in the bond line near the middle of the specimen. With successive yielding of the steel plate, higher shear stresses are created near the middle of the specimen. These are increased with the progress of yielding in the plate (due to increased plastic strains) with the location of maximum shear stress being shifted towards the end of the laminate. At higher loads (P = 184 kN) the magnitude of maximum shear stress in the middle of the specimen is higher than that at the laminate ends.

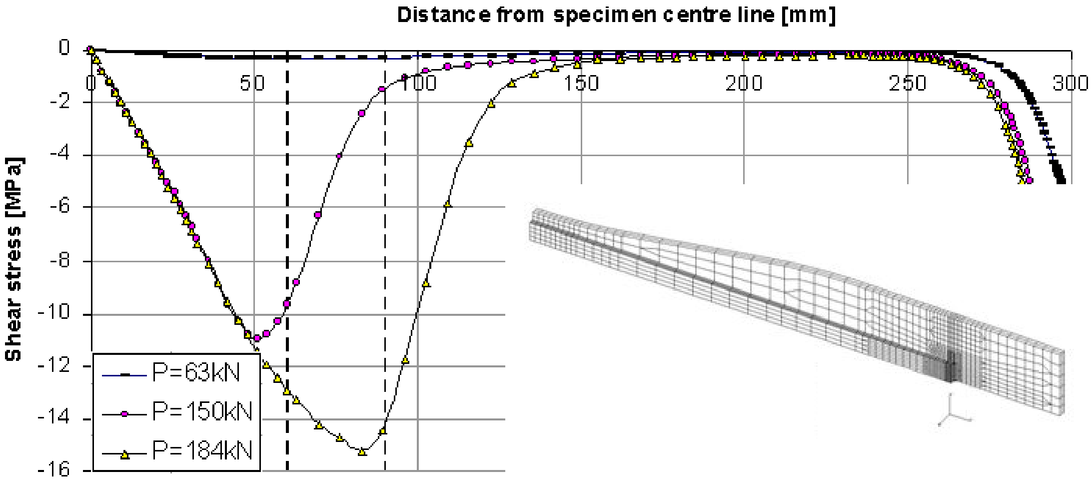


Fig. 6. The variation of interfacial shear stress along the bond line in one of the composite specimens (see Fig. 1-b). The vertical dotted lines show the progress of yielding from the middle the specimen (x=0).

The progress of yielding in the steel element resulted in successive debonding failure starting from the middle of the specimen and propagating towards the ends of the CFRP-laminate. Failure took place when the residual anchorage length (about 100 mm) was so short that the strength of the adhesive was exceeded, see Fig. 7.

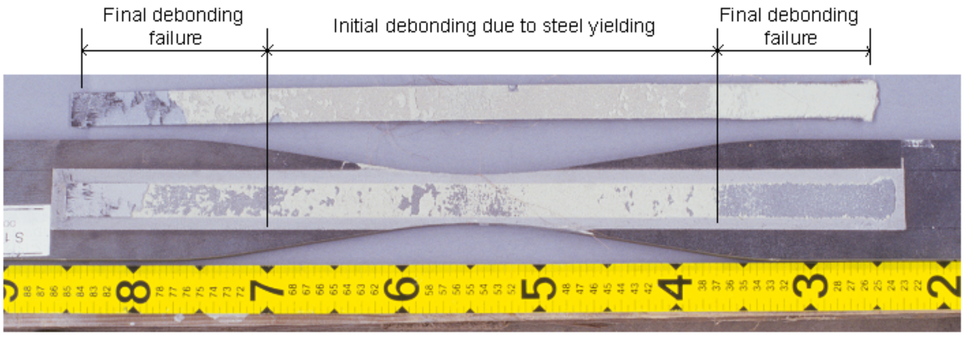


Fig. 7. Example of the composite elements tested to evaluate the effect of yielding in steel on the interfacial stresses in the adhesive joint.

6. Geometric modification of adhesive joints

As mentioned in previous section, one major problem when using bonded laminates to strengthen existing structures is the concentration of interfacial stresses, i.e. shear and peeling stress, near the ends of the laminate. One method, based on the stiffness revision of strengthening elements (i.e. adhesive layer and/or FRP laminate), is laminate-end tapering in which the laminate is cut through the thickness with a special angle, see Fig. 8.

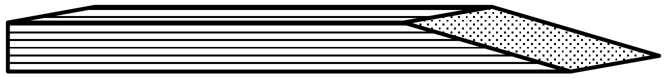


Fig. 8. Tapered laminate.

Tapering might be used in normal or reverse schedules, C2, C5 and C3, C6 respectively in Fig. 9. Either the schedules might be used with or without adhesive spew fillet at the end of the joint. The principle of laminate-end tapering is to obtain a more gradual transfer of the force from the structural member to the strengthening element and subsequently a reduction the interfacial stresses near the ends of the joint. It is believed that a more gradual transfer of the force would cause lower interfacial stress peaks along the joint. This will in turn increase the strength of the joint. Therefore, the use of laminate-end tapering in adhesive joints has been recommended in several design guidelines and recommendations (see for example [9]).

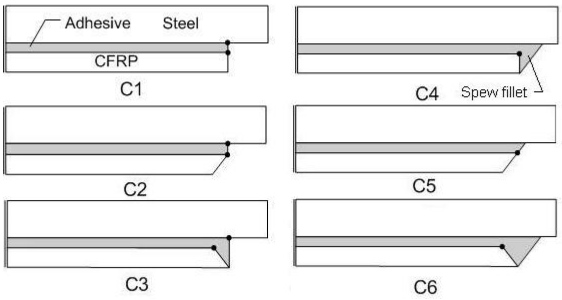


Fig. 9. Different schedules of adhesive joints.

The force transfer mechanism for some cases of modified and unmodified joints is illustrated in Fig. 10 by showing the stress flow in the joint.

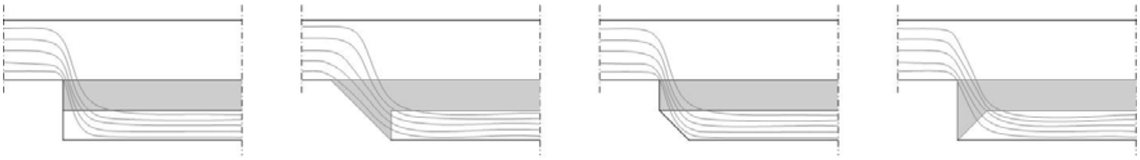


Fig. 10. Effect of modifications on stress flow in adhesive joints.

Although the positive effect of laminate-end tapering and spew fillets on reducing the interfacial stresses in adhesive joints has been the shown in several investigations [1, 10, 11, 12], there exist number of experimental evident that laminate-end tapering might actually result in lower joint strength compared to the untreated joint. A numerical and experimental study was conducted by Vallee et al. [13] to investigate the effect of normal tapering on the strength of double lap adhesive joints. One interesting conclusion following their study was that tapering does not improve the strength of the joint, even though it reduces the peak interfacial stresses. The authors' explanation for this phenomenon was that the favourable effect of tapering in reducing the interfacial stresses is counteracted by the reductive effect of tapering on the through-thickness shear strength of the laminate. A recently published experimental investigation of the behaviour of steel beams strengthened with bonded CFRP laminates [14] also indicates that the normal tapering of the CFRP laminate might reduce the strength of the reinforcement. The tapered specimens in [14] were manufactured using different lengths of prepreg laminates. It was found that the load-carrying capacity of a strengthened beam is lower when the bonded laminate was tapered in comparison to the case in which no tapering was used. The authors attributed this observation, however, to the smaller thickness of the adhesive layer in the specimen with tapered laminate in comparison to the control specimen. This would have caused a higher stress concentration in the former case.

In previous studies carried out by the authors of this paper [15, 16], the effect of different geometrical modifications at the ends of adhesive joints on the interfacial stresses in the joint was investigated. The FE-analysis was conducted on steel beams similar to those reported in this paper. Fig. 11 shows the model and examples of details at the modified end. The results indicated that in the absence of spew fillet, tapering of the end of the laminate might result in an increase of the peeling stresses in the joint, even though the shear stress near the ends of the joint is reduced. This holds true for normal as well as reverse tapering. The fact that the performance of adhesively bonded CFRP-laminates is more sensitive to the peeling stress might be a plausible explanation for the negative effect of tapering on the strength of the adhesive joints in some cases. The poor strength of CFRP-laminate in the through-thickness direction might be further lowered by tapering of the laminate end.

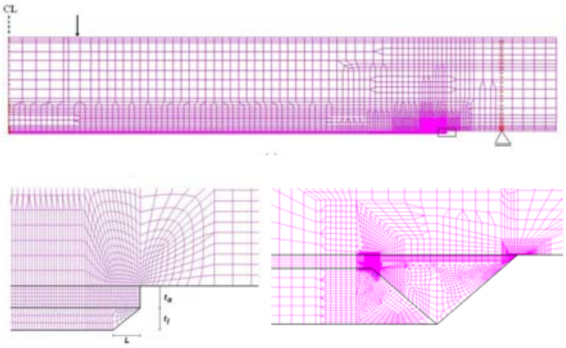


Fig. 11 FE-model used in the study.

The study was divided into two phases. In the first phase, the effect of laminate-end tapering with and without spew fillets was investigated. The main goal of this phase was to obtain a general understanding of the force transfer mechanisms in modified adhesive joints. The tapering angle and the angle of the fillet were chosen to 45 degrees, see Fig 12. Material and geometric properties of the joint constituents are listed in table 2.

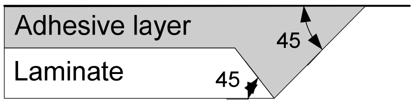


Fig. 12 Angle of the tapering and spew fillet.

Table 2: Different material and geometric properties considered in phase 1

Part	Laminate		Adhesive layer	
	Thickness [mm]	E-modulus [GPa]	Thickness [mm]	E-modulus [GPa]
Value	4	165	1	7

In phase 2 of the study the goal was to investigate the interactive effect of different material and geometric parameters on the distribution of the interfacial stresses in the joints. The effect of the tapering length was also investigated, and only joints without spew fillet were studied. The material and geometric properties considered in this phase are summarized in Table 3.

Table 3: Different material and geometric properties considered in phase 2

Parameter	E-modulus		Thickness		Tapering length
	Adhesive [GPa]	Laminate [GPa]	Adhesive [mm]	Laminate [mm]	(x laminate thickness)
Value	4	165	1	2	0
	5.5	200	2	4	1
	7	300			2
		400			4
					8
					16
					20

Phase 1

Fig. 13 shows the maximum values of the three main stress components (shear, peeling and principle stress) normalized with reference to the case with untreated joint end. All stress components are taken in the mid-thickness of the adhesive joint.

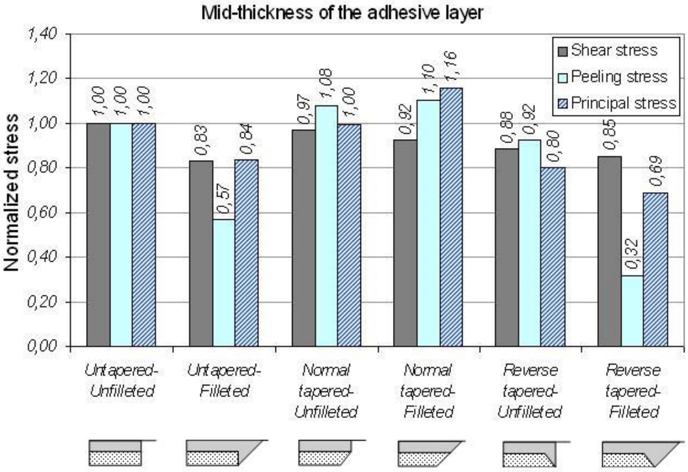


Fig. 13. Normalized maximum stress components for different configuration.

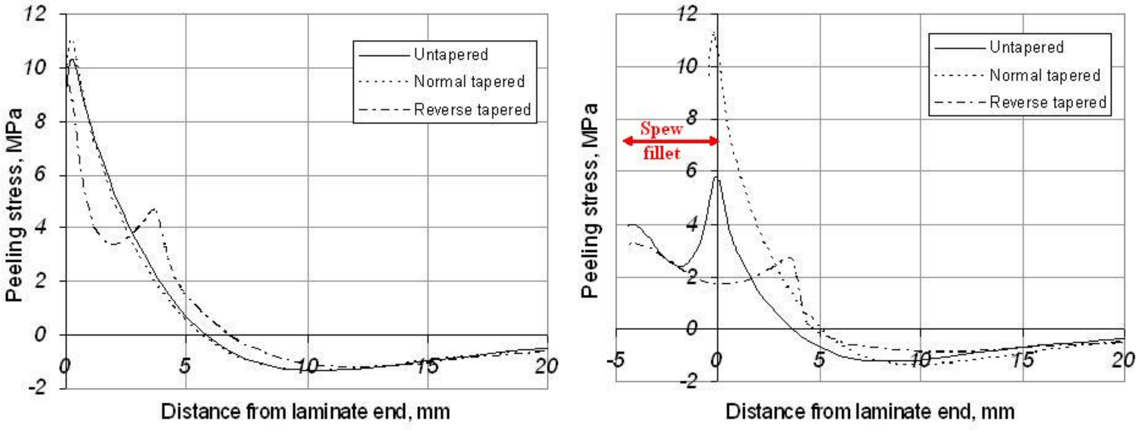
The following observations can be made considering the results in Fig. 13.

- For the case of untapered laminate, application of spew fillet has a considerable effect on reducing the maximum shear, peeling and principal stress at the mid-thickness of the adhesive layer. The reduction in shear stress is due to the more gradual transfer of the forces to the laminate. Also the maximum peeling stress in the joint is reduced as these two stress components are counter-dependent [17]. A comparison of peeling stress distributions between filleted and unfilleted joints is shown in Fig. 14.

- Normal tapering of the laminate, both with and without adhesive fillets, increases the peeling stress along the bond line. The maximum shear stress is, however, slightly reduced. The 45 degree normal tapering of the laminate end does not actually affect the stress flow in the joint significantly. Consequently, the maximum principle stress in the adhesive joint is not affected.

- Using reverse tapering reduces the maximum stress for all components. However, when an adhesive fillet is used in the joint, the reduction is more pronounced.

It is worth to mention here that all the results presented above are strictly applicable to the considered material property and the particular tapering and spew fillet geometries.



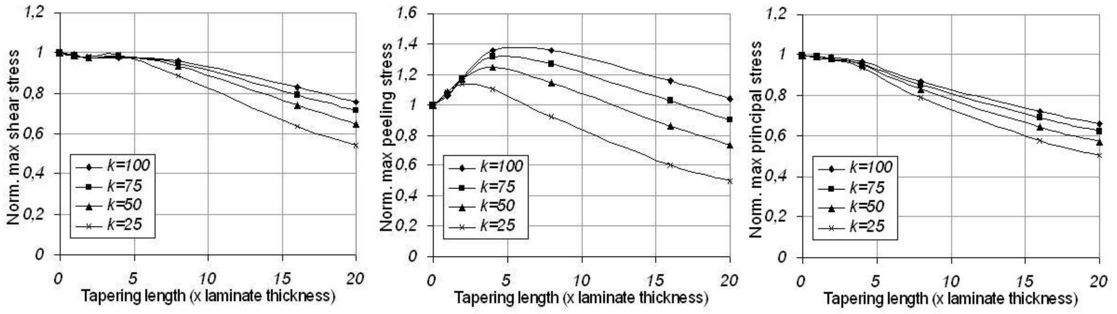
(a) (b)

Fig. 14. peeling stress distribution in joints with tapered and untapered laminates (a) without spew fillet (b) with spew fillet.

Phase 2

Considering the combinations of material and geometric properties listed in table 2, a total of 624 analyses were conducted. A categorization and comparison of the results showed that, for a specific geometric configuration (i.e. when the thickness of the adhesive and laminate is kept constant), the response of the joint to tapering is dependent on the ratio of the E-modulus of the laminate to the E-modulus of the adhesive (called here the stiffness ratio and designated as κ). It was generally observed that, for a specific geometry, joints with the same κ show the same variation in normalized peak stress values for different stress components.

Fig. 15 shows the maximum value of the three main stress components in the joint as a function of the tapering length for joints with normally tapered laminates. To ease the comparison, the results are normalized with reference to the case with unmodified configuration. It is seen that normal tapering does not affect the shear stress in practical tapering lengths (less than 5 times the thickness of the laminate). It might be observed that depending on the stiffness ratio, κ, tapering might increase the peeling stress. The principle stress is on the other hand reduced, but the magnitude of reduction is very small for practical tapering lengths.

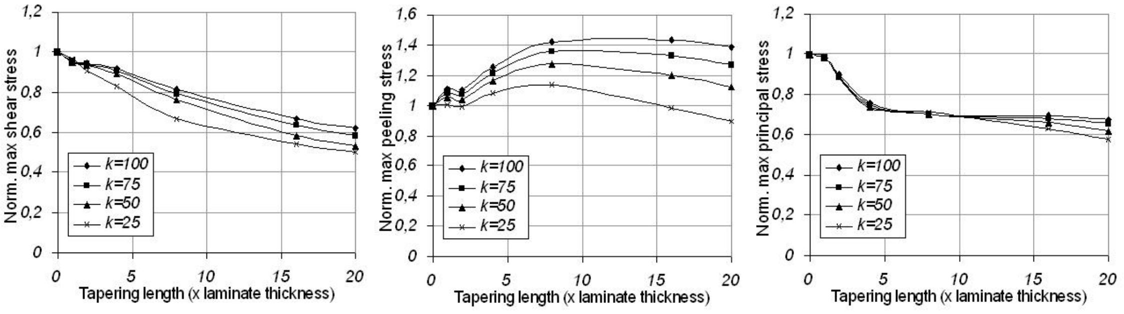


(a) (b) (c)

Fig. 15. Influence of stiffness ratio on the effect of normal tapering on (a) shear stress, (b) peeling stress, (c) principal stress. Results for joints with adhesive layer thickness of 2 mm.

Reverse tapering schedule is more effective in reducing the maximum shear stress in the joint in comparison to normal tapering, see Fig. 16. Again it is observed that depending on stiffness ratio, reverse tapering might increase the peeling stress component. Reverse tapering is also more effective considering the reduction in maximum principal stress.

Finally, the results of the analyses show that the positive effect of tapering, whether normal or reverse, is also dependent on the thickness of the laminate and that of the adhesive layer. The benefit of tapering in term of reduced principle stress in the adhesive joint is more pronounced in joints with thinner adhesive layer and when thicker laminates are used in the joint.



(a) (b) (c)

Fig. 16. The influence of the stiffness ratio in reverse tapering on (a) shear stress, (b) peeling stress, (c) principal stress.

7. Design considerations

Composite materials have been used in strengthening concrete structures for decades. Today, there exist numerous guidelines and recommendations on the design of concrete members strengthened with bonded composite materials. In concrete applications, the performance of the strengthening scheme is usually governed by the strength of the concrete. Failure in concrete beams strengthened with bonded CFRP-laminates, for example, is often triggered by failure of the concrete cover due to the poor strength of concrete in tension. The situation is, however, more complicated in steel beams. Steel has superior strength in comparison to conventional adhesives used in strengthening applications and the through-thickness performance of the CFRP-laminate is also relatively low. In a steel beam strengthened with bonded CFRP-laminate, one can distinguish four different possible failure modes, see Fig. 17:

A. Debonding along the steel-adhesive interface

B. Cohesive failure of the adhesive

C. Debonding along the adhesive-CFRP interface

D. Interlaminar failure of the CFRP-laminate

Of course, rupture of the laminate is also possible. This failure mode is, however, easier to design for. Load effects in the CFRP-laminate (usually axial stresses or strains) can in most cases be easily calculated and the ultimate tensile strength of CFRP-laminate is often known or can be obtained by simple testing.

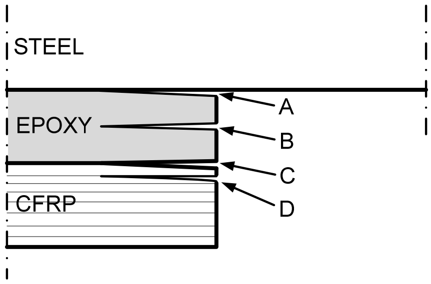


Fig. 17. Different failure modes in steel beams strengthened with adhesively bonded CFRP-laminates; A) Interfacial failure between steel and adhesive, B) Cohesive failure, C) Interfacial failure between Adhesive and CFRP and D) Delamination of CFRP laminate.

In the design of adhesive joints, one usually distinguishes between two main approaches: stress-based methods and energy-based methods. In the first approach, the stresses components, usually shear and peeling stresses are obtained by simplified closed-form analytical solution. One of two main criteria can then be applied. Most commonly, the shear and peeling stresses are combined to a principle stress, which in turn is compared to the *tensile strength of the adhesive,* see Equation 1. The relation between the shear stress and the peeling stress is thus not considered as a design parameter. In the second approach, some kind of interaction formula is used to account for the difference in load effects (shear and peeling) and the corresponding difference in material strength (Equation 2). In both approaches, the calculation of load effects and the values of material strengths are generally made with reference to the adhesive only.

$$\sigma_1 = \frac{\sigma}{2} + \sqrt{\left(\frac{\sigma}{2}\right)^2 + \tau^2} \leq \overline{\sigma} \qquad (1)$$

$$\left(\frac{\sigma}{\sigma_{ult}}\right)^{\alpha} + \left(\frac{\tau}{\tau_{ult}}\right)^{\beta} \leq 1{,}0 \qquad (2)$$

Debonding failures along the steel-adhesive and adhesive-CFRP interfaces are more difficult to account for in design. The strength of these two interfaces is highly dependent on “quality factors” such as surface preparation of the adherents and the quality of the workmanship. Owing to material and geometrical discontinuities, an accurate estimation of the load effects along these two interfaces is also rather difficult to achieve.

Cohesive failure in the adhesive is govern by the strength of the adhesive used. The situation is similar for delamination in the CFRP-laminate, see Fig. 18. Adhesives and CFRP-laminates have usually different shear and tensile strengths (the shear strength being several times higher than the tensile strength). Design criteria based on some kind of equivalent or principle stress are therefore not expected to yield good results, when compared to the real strength of such joints.

Fig. 18. Example of delamination of a CFRP laminate bonded to a steel member.

Efforts have been made in the ongoing research programme to study the behaviour and strength of adhesively bonded CFRP-laminate and to develop design rules suitable for the application on steel elements strengthened by means of bonded composite materials. The research work is still ongoing and some tests have not been fully evaluated. Nevertheless, in the following text, parts of the work done so far are highlighted.

It is believed that debonding failures along the steel-adhesive and adhesive-CFRP interfaces can and should be avoided by specifying clear requirements on surface preparation and good workmanship. It was also found that the selection of strengthening systems with good material compatibility is very vital to avoid these failure modes. The bond strength of CFRP-laminate bonded to steel could be examined by means of simple three-point bending tests. These small-scale tests give valuable information on the interfacial strength of any steel-CFRP joint and the effect of various parameters can be easily investigated.

In design for cohesive failure in the adhesive and interlaminar failure of the CFRP-laminate, the strength of these materials in shear and peeling need to be determined. In the current investigation, DCB- and ENF-specimens have been employed to obtain the relevant material strength data for these two failure modes. These tests can be conducted with reference to the adhesive and the laminate separately. The tests provide then the strength of the adhesive and the laminate in pure tension and pure shear, respectively. Also the fracture energy for the two materials is obtained for Mode I and Mode II loading. These material data can then be used in any energy-based design approach or in fracture-mechanics based FE-analysis of the strengthened members using suitable interface elements.

8. Linear elastic fracture mechanic method

The energy based method is an approach of the linear elastic fracture mechanics. The characteristic of the energy release rate is that it considers the energy released during the propagation of the crack along the adhesive joint, and the methods inherently take account to the existence of stress discontinuities. The design philosophy is that the fracture energy release rate (G) during propagation of the crack is obtained and compared with the critical energy release rate (G_C) determined using standard fracture mechanic test. Thus, the design criterion is that $G_I \geq G_{IC}$.

The advantages of the energy based method are that the formula is easier to use and the detailed stress distribution does not need to be determined. On the other hand, it is not applicable to beams of non-constant cross-section and it is difficult to estimate a relevant size of the initial crack. Besides this, fracture mechanics is not widely used in applied structural engineering due to its complexity.

9. Conclusion and future work

A wide range of issues related to the strengthening of steel members with bonded composite laminates were discussed. The experience and outcomes of the ongoing research at Chalmers University of Technology on this subject were presented. In the following text, the most essential results and conclusions are summarized along with a view of the needs for further research.

- In the area of material properties, a good knowledge is achieved for mechanical properties of the composite materials and adhesives. However, there is number of questions and uncertainties about the long-term behaviour of the strengthening materials and their combination. Further research is needed on this subject especially for strengthened steel members where there is an inconsistency between the thermal expansion properties of steel and composite laminates.

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Bonding of CFRP-laminates might be an effective repair method to restore the load-carrying capacity of deteriorated steel elements, due to corrosion for example. For strengthening purposes, the magnitude of increase in the moment capacity of steel beams is limited by the capacity of the beam to yield in compression. For beams with double symmetrical I-sections, a strengthening effect of about 20% is the maximum which can be achieved. For higher increase in moment capacity, the compression part of the beam also needs to be strengthened.

- Experimental work shows that the strength and performance of the adhesive joints is highly dependent on quality of surface preparation and workmanship. It is possible to avoid failure modes related to debonding along the interfaces of the adherents by ensuring good surface preparation and good material compatibility.

- Although the design method for strengthening of concrete structures using composite laminates is well established and documented, the resources for strengthening steel members are very limited. This is mainly due to lack of knowledge about the failure modes of the reinforcement is steel members. The existing failure criteria are based on assumption of cohesion failure. According to observations from the experimental work, such assumption should be questioned since the most critical positions for initiation of failure in the joint are adjacent to the interfaces. To be able to develop a suitable design criterion it is necessary to have a model to evaluate the stresses at critical positions, i.e. point of stress concentration or discontinuities, and then predict the failure mode of the joint.

- The non-uniform through-width interfacial stress distribution is another important issue which should be considered in design criterion since analytical solutions do not consider this variation and usually underestimate the interfacial stresses.

Tapering of the laminate-end to reduce the interfacial stress should be done regarding to two important facts. First, depending on material and geometric properties tapering might result in higher peeling stresses in the joint. Second, through-thickness strength of the laminate might be reduced by tapering. Using tapering, the role of the spew fillet becomes important and special precautions should be taken for protection of the fillet.

The presented results are based on FE analysis of the adhesive joints. The experimental work to investigate the effect of joint modification on stress distribution is ongoing.

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