CHAPTER 6

CONCLUSIONS

6.1. Introduction

The use of externally bonded plates made of Fiber Reinforced Polymers for rehabilitating or upgrading existing concrete structures has gained widespread acceptance thanks to the ongoing research all over the world. However, the significant increase in strength and stiffness that can be achieved by applying composite materials is often offset by some premature failures involving the laminate peeling-off.

The main objective of this research has been the analysis of the stress transfer between concrete and laminate and afterwards the development of a design or verification method to avoid the premature laminate peeling-off ensuring a good performance of the strengthened structure. The reliability of this method has been checked by means of a bending test database.

In this chapter, the main conclusions drawn from the work presented on this dissertation are summarized. In addition, some proposals for future research are suggested.

6.2. Concluding remarks

6.2.1. Conclusions about the suitability of the FRP strengthening method

From the review of the existing experimental line of investigation, including the experimental program performed by the author at the Structural Engineering Lab of the Technical University of Catalonia (UPC), the following conclusions are drawn:

1) With regards to the existing experimental studies, brittle failure modes appear when reinforced concrete elements are strengthened with externally bonded plates. These premature failure modes involve the debonding of the laminate and prevent the reinforced concrete section from reaching its ultimate capacity. 86% of beams assembled in the bending test database, shown in §2.2.4, failed due to premature laminate debonding.
2) According to tests observations, laminate peeling-off initiates at two main locations: at the plate end, and along the span at critical sections of cracking.
3) During the current research, an experimental program has been performed by the author as a tool to identify the behavioral trends that should be considered in design calculations. Except for Beam 1/D, where a lack of anchorage was observed, the remaining beams failed due to the laminate peeling-off which initiated near flexural or shear cracks. Data results showed that the midspan laminate strain at failure was always lower than 0.40% for Beam group 1 and lower than 0.55% for Beam group 2. Both strains are lower than the recommended value of some guidelines to prevent peeling failure, which is the minimum of half of the laminate ultimate tensile strain (0.80% in this case) and five times the steel yielding strain (1.30%, from the tensile test of internal steel rebars). Thus, a more accurate design method to prevent peeling failure should be developed.
4) In addition, the maximum strain attained by the laminate is less than half of its ultimate strain. This indicates the under-utilization of the properties of the advanced composite materials.
5) Increasing the laminate length to cover the entire span allows the failure load to increase but does not prevent the laminate peeling failure. The main notable observation is the shift of the debonding initiation point from the laminate end to a location near flexural or shear cracks.
6) The use of external anchorage devices delays the peeling effect and provides an increase in strength. In Beams 2/A and 2/B, the bonded anchorage held the laminate after its debonding and during its sliding, until the rupture of the anchorage sheet. If fibers in the external anchorage were placed in both longitudinal and transversal direction, the failure load would have been increased. Although an improvement of the beam response was observed in both Beams 2/A and 2/B, the use of external anchorage devices has not been discussed later on in this research.
7) As shown by the response of Beam 1/A of the Experimental Program and confirmed by the preloaded beams assembled in the database, beams that have been preloaded before bonding have an equivalent performance at failure as beams strengthened without any previous load application.

8) The application of laminates in saw-cut slots in the concrete cover improves the bond between concrete and laminate, allowing greater strains prior to peeling. However, due to the reduced cross-section of these laminates, many saw-cuts should be done on the tensile face of the beam to achieve a significant increase in beam strength. In other words, the characteristic tensile strength capacity of a typical laminate, designed for this application, measuring 10 *mm* x 1.4 *mm*, is equivalent to that of a 6 *mm* steel rebar.

6.2.2. Conclusions on the reliability of the existing theoretical models in predicting peeling failure

In §2.3 of Chapter 2, the existing simplified methods to predict peeling failure have been presented. Their reliability in predicting the failure load have been checked by means of a statistical analysis (§2.4) of the ratio between the experimental failure load and the predicted ultimate load for the bending test database. Some conclusions are listed below:

1) The truss model of Colotti and Spadea (2001), the shear capacity based models of Oelhers (1992) and Ali et al. (2001), and the concrete tooth model of Raoof et al. (1997, 2000a, 2000b, 2001) were developed to prevent peeling failure due to the effect of flexural or shear cracks. All models performed similarly regardless of the peeling initiation point.
2) The shear capacity based model of Ali et al. is the best statistically performing model in terms of predicting the failure load with a conservative mean and median value and the lowest coefficient of variation. However, when analyzing steel plated beams alone, Ali et al.'s model gives a mean and a median of 0.85 which is the limit between the appropriate and low safety levels according to the Demerit Points Classification of Collins (2001).
3) Despite the good performance of the concrete tooth model of Raoof et al. some of their assumptions are questionable. Even though Raoof et al.'s model was designed to predict peeling failure in the concrete cover, it surprisingly shows a better performance for plate end shear failure.
4) By applying the Demerit Points Classification of Collins, Ali et al.'s model gets the lowest score, followed by the concrete tooth model of Raoof et al. and then, by the truss model of Colotti and Spadea.
5) The shear capacity based models of Jansze (1997) and Ahmed et al. (2001) were designed to prevent plate end shear failure. Results for both models are similar for both peeling failure in general and peeling failure due to cracks. Obviously, the performance of these models improves for those tests that failed by plate end shear failure. Since Ahmed et al. modified Jansze's model to make it suitable for CFRP plates, it gives better predictions for this type of reinforcement in most cases. However, it seems necessary a further readjustment of this formulation because of the uncertainties derived from some empirical parameters.
6) Most existing theoretical studies, for instance linear elastic models, were focused on predicting peeling failure at the plate end. Linear elastic models were developed to obtain the maximum shear and normal interfacial stresses, which are combined and compared to a failure criterion.

7) In general, a large scatter is observed for all linear elastic models. This large scatter makes these models unsuitable to prevent peeling failure at any location, even at the laminate end.
8) By choosing those tests that failed by end peeling from the database, a linear elastic analysis combined with the failure criterion of Kupfer and Gerstle (1973) yields to more conservative results than the Mohr-Coulomb criterion. The linear elastic analysis combined with the Mohr-Coulomb criterion given by Chaallal et al. (1998) and Ziraba et al. (1994) have been identified as the worst performing models in terms of reliability and safety of its predictions.
9) A linear elastic analysis is not able to simulate the shear stress distribution along a cracked beam because it wrongly predicted the shear stress near cracks.
10) Since the stress transfer through the interface between concrete and laminate is the main issue in the correct performance of a strengthened structure, the understanding of the interface behavior can be improved by means of Non-Linear Fracture Mechanics theory.

6.2.3. Conclusions from the analysis of the interface behavior in a pure shear case

By applying Non-Linear Fracture Mechanics, the formation and propagation of an interfacial crack that causes the laminate peeling-off in a simple case of a pure shear specimen has been studied in Chapter 3. Some conclusions are summarized as follows:

1) By assuming a bilinear bond-slip relationship in the solution of the differential equation of Volkersen (1938), the interfacial shear stress and laminate tensile stresses have been obtained in the different stages of crack propagation.
2) The debonding process starts at the load application point and propagates towards the free laminate end. Initially, while increasing the applied load, the interface behaves linear elastic (Stage 1).
3) Once the maximum shear stress is reached at the loaded laminate end, microcracks appear between the load application point and the maximum shear stress location (Stage 2). In this area, the stress transfer is still possible by aggregate interlock. This post-peak behavior is described by the descending branch of the bond-slip relationship.
4) With increasing values of the applied load, the maximum shear stress location moves towards the free laminate end. In a long laminate, the maximum sliding is attained at the load application point before the maximum shear stress reaches the free laminate end. On the contrary, in a short laminate, the maximum shear stress reaches the free laminate end before sliding at the loaded end reaches its maximum value, s_{L0}. The crack distance between both situations is known as the limit between a short and long laminate. In addition, the limit between a short and long laminate can be defined as the length from which an increase in the bonded length does not imply an increase in the transferred force.
5) In a long bonded length, a real macrocrack appears when the maximum sliding is attained at the load application point (Stage 3a). As the debonding process evolves, the macrocrack propagates towards the free laminate end, and the transferred force decreases. When the maximum shear stress reaches the free laminate end, Stage 3b starts. The macrocrack length remains constant and equal

to the limit length between a short and long laminate. Meanwhile the shear stress distribution starts decreasing to zero. The zero shear stress value is reached at every location at the same instant. At this point, the laminate completely debonds in a brittle manner.

6) In a short bonded length, once the maximum shear stress reaches the free laminate, Stage 2b starts. The shear stress distribution starts to decrease along the complete bonded length to a zero value which is reached at the same instant at every location. At this point, the laminate peels-off. Since the transferred force is the sum of shear stresses, a decreasing trend is observed in the transferred force as well.
7) Once the transferred force starts to decrease for both short and long bonded lengths, the evolution of the debonding process is only possible when the sliding and not the applied force is controlled at the loaded laminate end. Any attempt to increase the applied force will lead to a sudden laminate debonding.
8) For long bonded lengths, the maximum transferred force is attained just before the macrocrack opens, that is, in the surroundings of the transition between Stage 2 and Stage 3a. For short bonded lengths, the maximum transferred force is attained when the maximum shear stress reaches the free laminate end (at the beginning of Stage 2b).
9) For both short and long bonded lengths, the maximum transferred force can be written as a function of the fracture energy, given as the area below the bond-slip curve.
10) The application of the developed model requires the definition of three parameters which are: the maximum shear stress and the fracture energies of Zones I and II of the bond-slip relationship. All of them depend mainly on the concrete and adhesive properties.
11) The statistical analysis shows a good performance of the developed method when predicting the peeling failure load in single or double shear tests that were compiled in the database presented in Chapter 2. The average ratio between the experimental and predicted failure load was 1.04 with a coefficient of variation of 0.34.

6.2.4. Conclusions from the analysis of the interface behavior in a beam subjected to transverse loads

In Chapter 4, the formulae of a pure shear specimen have been extended to the case concerning a cracked beam subjected to transverse loads. From this study, the following conclusions are drawn.

1) The main difference in the governing equation between the case at hand and that of a pure shear case is the presence of a term related to the slip reduction due to the strains on the support. By neglecting this term, the differential equation governing the laminate leads us to a pure shear case scenario.
2) The most conservative approach is to neglect the influence of tensile concrete between two cracks. This assumption simplifies the solution because of the homogeneity of the governing differential equation. However, the concrete's contribution in tension cannot be neglected between the laminate end and the

nearest crack. It has a significant influence on the shear stresses at the laminate end since this section often remains uncracked.

3) The solution of the differential equation in the linear elastic branch of the bond-slip relationship is similar to that obtained by linear elastic models applied at the laminate end as described in Chapter 2.
4) In Chapter 4, by applying the appropriate boundary conditions, the interfacial shear and laminate tensile stress distributions, as well as the sliding between laminate and support have been calculated for different load levels along the beam span, either between cracks or at the laminate end.
5) Although the developed formula helps to understand the interfacial crack propagation, it seems awkward for design purposes. A simple procedure for predicting the peeling failure in verification or design calculations should be derived using the formulae of Chapter 4 as a base.
6) In a pure flexure case, shear stresses between two adjacent cracks are not required for equilibrium and are exclusively generated by tension-stiffening. The interfacial shear stress distribution is skew-symmetric at the midpoint between two cracks. Since there is no increment on the laminate tensile stresses between two adjacent cracks, the transferred force between these points is zero, even if it is non-zero from each crack to the midpoint of the crack distance.
7) When transverse loads are acting between two adjacent cracks, shear stresses are required for both equilibrium and strain compatibility and no symmetry is observed in the interfacial shear or laminate tensile stress distributions.
8) Between two adjacent cracks, the debonding process propagates from both crack tips towards the point of zero shear stress which is placed along the crack spacing. Initially, the interface between two flexural or shear cracks behaves linear elastic (Stage 1). Once the maximum shear stress is attained near a flexural or shear crack, part of the interface will be on the descending branch of the bond-slip relationship (Zone II) and microcracks will appear between the maximum shear stress location and the nearest crack (Stage 2a.1 or 2a.2). The remaining points along the crack distance will continue behaving in a linear elastic manner.
9) As the applied load increases, the zero shear stress location moves toward the less loaded crack and the interface length in Zone II increases.
10) In a general case, the laminate debonding between two cracks I and J is initiated when the maximum sliding is attained at the most loaded crack (crack J). A macrocrack thereafter opens and propagates towards crack I (Stage 3a). Total laminate peeling-off does not occur until the maximum sliding reaches the less loaded crack.
11) If the maximum shear stress reaches the less loaded crack before the maximum sliding is attained in crack J, the crack distance is defined as a short distance. In a usual load control situation, when the maximum shear stress reaches the less loaded crack, the laminate suddenly debonds. In case the slip is controlled instead of the applied force, the shear stresses will be progressively reduced with increasing slip values at both crack tips (Stage 2b). However, this phenomenon is only of academic interest.
12) While the macrocrack is growing during Stage 3a in a long crack distance, the maximum shear stress can reach crack J. At this point, in a usual load control situation, the laminate debonds from the support. In a hypothetical situation where slip control is possible (Stage 3b), the shear stresses will be reduced in a similar fashion as in Stage 2b. The evolution of both stages and the macrocrack

growth depend mainly on the internal steel state. Note that the remaining bonded length during this stage is equal to the limit between a short and a long crack distance.

13) For short crack distances, the maximum transferred force is attained at the beginning of Stage 2b when the maximum shear stress is reached in crack I. At this point, the shear stresses are transferred along the whole crack distance.
14) For long crack distances, the maximum transferred force is reached when the shear stress is at maximum in crack I, commonly at the beginning of Stage 3b. In this case, a macrocrack has appeared and has propagated already during the previous Stage 3a. Thus, the shear stress transfer is only possible along the remaining bonded length, a length equal to the limit between short and long crack distances.
15) The description of the debonding process along the distance between the laminate end and the closest crack is similar to that of a pure shear specimen. When neglecting the concrete’s contribution, the formulae for interfacial shear and laminate tensile stresses derive into the equations developed in Chapter 3.

6.2.5. Conclusions from the proposal for design or verification

In Chapter 5, a design and verification proposal to prevent peeling failure when strengthening a beam subjected to transverse loads is given. This proposal is based on the maximum force transferred along the crack distance which was calculated in Chapter 4 for both short and long crack distances. The maximum transferred force establishes a limit on the shear force acting on the most loaded crack. The maximum shear force that causes the laminate peeling-off, for any possible bending moment value, can be calculated as a function of steel yielding. From the calculated maximum shear force and bending moment values, a peeling limit relationship is obtained. This relationship represents the basis of the design and verification procedure described in Chapter 5. Some observations of the peeling limit relationship are listed below.

1) First, the crack distance should be estimated. The guidelines of the FIB Task Group 9.3 FRP (2001) can be used for this purpose.
2) Since the maximum transferred force depends on the laminate bonded length, the limit between a short and long crack distance should be obtained for each bending moment to determine if the crack distance associated to the limit shear force is either short or long.
3) If the crack distance is identified as short, the maximum shear force will depend on the estimated crack distance. On the contrary, if the crack distance is identified as long, the maximum shear force will depend on the remaining bonded length, which is equal to the limit between a short and long crack distance.
4) The maximum shear force has an upper limit given by the following condition: the bending moment on crack I should always be higher than or equal to zero.
5) In addition, the maximum bending moment also has an upper limit which is the lowest value of either the ultimate bending moment that causes concrete crushing or laminate rupture, or the bending moment that causes peeling failure in a pure flexure case.

6) For short crack distances, the maximum shear force decreases linearly with increasing values of the bending moment on crack J. The slope of this relationship varies depending on the internal steel state in both cracks I and J.
7) For long crack distances, the linear relationship becomes non-linear. However, when using a multi-linear approach, the committed error is negligible.
8) In any case, to simplify the design or verification procedure, the maximum shear force-bending moment relationship that prevents peeling failure can be approached by a multi-linear function.
9) With this approach, seven possible cases can be obtained depending on the point where the laminate transforms from short to long, and on the intersection of the upper limit with the maximum shear force-bending moment relationship.

The verification procedure (§5.3) consists in ensuring that the force transferred between the two adjacent cracks in the most unfavorable location is lower than the theoretical maximum transferred force. In other words, the shear and bending moment on the most unfavorable cracked section should be lower than the peeling limit relationship. By accomplishing this condition, a sudden laminate debonding originated by the effects of cracks will be avoided.

The design procedure has been developed in §5.4. First, the laminate area necessary for flexural strengthening should be calculated. Then, peeling failure should be checked according to the maximum shear force-bending moment relationship described above. It is a relatively simple iterative method, which only requires moment-curvature analysis among some simple hand calculations.

Both design and verification procedures should prevent not only peeling initiated near cracks but also peeling initiated at the laminate end. The transferred force between the laminate end and the nearest crack should be lower than the theoretical maximum transferred force. If this condition is not accomplished, a local debonding at the laminate end will occur. This local debonding does not imply the complete laminate peeling-off. To know if the debonding is localized or not, the element between the first two cracks at the laminate end should be checked. If the transferred force is lower than the maximum possible value, peeling will initiate due to the effect of cracks and a local debonding will be observed at the laminate end. In the opposite situation, in order to avoid the complete laminate debonding, the maximum shear force that prevents peeling failure from occurring near cracks should be reduced.

The reliability of the verification procedure has been successfully checked by predicting the peeling failure load of the tests compiled in the database. Some conclusions are summarized below:

1) Since no crack distribution is available in the majority of analyzed tests, the verified section was the shear span end, that is, the load application point.
2) The concrete's contribution in tension can be neglected when calculating the maximum shear force-bending moment relationship without resulting errors.
3) By applying the proposed method in the verification of assembled tests that failed by peeling but without distinguishing the initiation point, the average ratio between tested and predicted shear force was 1.26 with a coefficient of variation of 0.26. By applying the Demerit Points Classification of Collins (2001), the score is much lower than the models studied in Chapter 2.

4) Furthermore, the model shows an even better performance when studying peeling failure due to the effect of cracks with a mean value of 1.23 and a scatter of 0.25. The percentage of tests in the appropriate safety range is 67.3%. Only 5.3 percent of tests are in a low safety level.
5) A characteristic lower bound of the ratio $V_{\text{exp}}/V_{\text{pred}}$ is obtained as 0.87 the median value.
6) An oscillation of 20% when estimating the fracture energy does not have a significant influence in the calculation of the peeling shear force vs. bending moment relationship.
7) Since some intermediate cracks were observed at high load levels in some of the compiled tests, the influence of crack distance was studied. The differences in predictions in terms of mean and coefficient of variation are not very noticeable. However, the author suggests calculating the crack distance by using the FIB Task Group 9.3 FRP (2001) for those tests where no external load was applied before plate bonding.

6.3. Recommendations for future research

The author believes that the study described here is far from complete and there are still questions that need to be answered. Future research should address the issues mentioned below:

1) The key issue is to continue providing a scientific assessment of the mechanisms related to the peeling phenomena in order to find a solution that prevents this premature failure and take advantage of the tensile properties of advanced composites.
2) Extensive research should be done to determine the experimental maximum transferred force between two adjacent cracks.
3) Although the author believes that the total fracture energy includes the effects of interfacial normal stresses, and some authors (Malek et al., 1998) assure that these stresses do not have significant influence between cracks, the distribution of interfacial normal stresses should be studied to confirm this issue.
4) More experimental research should be performed on beams strengthened in flexure in a three-or-four point bending configuration. The origin of laminate debonding and the way of propagation should be studied by affixing the silver paint method mentioned by Ulaga et al. (2002). In addition, crack width should be measured, because it gives information about the laminate sliding under each crack.
5) When applying Non-Linear Fracture Mechanics in a pure shear specimen, the interface is loaded primarily in shear and hence the propagation mode of failure can be assumed as shearing mode II. In a beam subjected to transverse load, the most common case is a combination of some of these fracture modes, known as mixed mode cracking. To simplify the problem, in this work the interfacial normal stresses were neglected, assuming mode II crack propagation. In addition, the effect of these normal stresses is assumed to be included in the total fracture energy. However, a more realistic approach will be to consider failure mode III in the derivation of the formulae.

6) As mentioned in Chapter 4, the interfacial crack propagation process was found by assuming that there is a slip between concrete and the external reinforcement and that there is perfect bonding between concrete and the internal steel rebars. However, in reality, there is also a slip between the concrete and the internal reinforcement. A more accurate description of the problem would be obtained by considering this slip in the derivation of the governing equation for interfacial stresses.
7) Experiments have shown that external anchorages delay the appearance of the peeling phenomena. The effect of these devices in the formulation described in Chapter 3 and 4 should be analyzed.
8) The influence of the original stress situation before applying any external reinforcement should be studied.
9) The vast majority of studies are related to short term behavior of plate bonding. However, long term performance of the technology of bonding FRP plates to the tension face of concrete structures should be assessed.

From the present dissertation, some extensions for the conducted research that were initiated but not completed due to problems that emerged during work are summarized beneath.

1) The performance of an experimental program on double shear tests with enough instrumentation to compare the shear stress distribution to the theoretical approach derived by using Non-Linear Fracture Mechanics, and to evaluate the fracture energy.
2) The evaluation of the stress concentration around cracks and at the laminate end by means of a Finite Element Analysis, assuming a bilinear bond-slip relationship for the interface and modeling concrete by discrete cracking.

Finally, there are many topics related to the externally bonded reinforcement that have been already studied in the literature which are not the object of this work, but which should be completed, like shear strengthening of beams by using bonded laminates, prestressing the laminates before bonding, and the problem of fire in bonded connections where the glass transition point of the adhesive matrix can be reached within a few minutes of a standard fire.