CHAPTER 1

INTRODUCTION

1.1. Introduction

The repair and reinforcement of existing structures has received a significant emphasis over the past few years due to infrastructure aging. After some time in service, concrete structures may be damaged, so they may be in need of repair due to the loss of carrying capacity. Alternatively, existing structures may need to have their resistance or stiffness upgraded to withstand an increased load demand or to eliminate structural design or construction deficiencies.

The technique for strengthening existing structures by bonding steel plates to the tension face of beams or girders was initiated with the development of strong epoxy adhesives in the late sixties and early seventies. The additional bonded reinforcement enhances the performance under service loads by reducing deflections and cracking, and increases the ultimate strength.

The first recorded case of field application of steel plate bonding was in 1964, in an apartment complex in Durban, South Africa, where part of the internal reinforcement was accidentally omitted during construction, (Raoof and Zhang, 1997).

Although steel plate bonding has been widely used in many countries up to now, steel plates present some disadvantages mainly in terms of weight and corrosion adversely affecting the bond between the plate and the support. To solve both handicaps, Fiber Reinforced Polymers (FRP) were introduced in the strengthening field instead of steel plates because of their high strength-to-weight and stiffness-to-weight ratios as well as their corrosion resistance. The low density of FRP laminates leads to an easy handling that reduces installation costs. In addition, the FRP laminates can be applied while the structure is in use with negligible changes on both member dimensions and self-weight. Three types of FRP are commercially available: glass (GFRP), aramid (AFRP) and carbon (CFRP) in the form of thin unidirectional strips made by pultrusion or flexible sheets made of fibers, in one or more directions, sometimes pre-impregnated with resin.

FRP materials were used primarily in the aerospace and defense industries rather than in civil engineering due to the prohibitively high cost of raw materials and manufacturing process. Although FRP are around ten times more expensive than mild steel, material costs usually only constitutes around 20% of the total cost of a strengthening project, with the remaining 80% as labor costs that are considerably reduced when applying FRP laminates (Garden and Hollaway, 1997).

The first application of a carbon fiber/epoxy laminate as an external reinforcement dates from 1991, on the Ibach Bridge near Lucerne in Switzerland (Meier, 1995) (see Figure 1.1).

Figure 1.1. Strengthening of the Ibach Bridge in 1991 in Switzerland. (Cress, 2000)

Up to now, there is a variety of worldwide on-site applications using composite materials for rehabilitation and retrofit of structural elements of bridges and buildings (see Figure 1.2). However, their use is distantly based on a complete rational design.

Figure 1.2. Application of composite materials for retrofitting concrete structures such a bridge deck, a slab or a column. (Bettor MBT, Degussa Construction Chemicals España, S.A.)

1.2. Objectives

1.2.1. Problem statement

From the early nineties, extensive investigations of the structural behavior of FRP-strengthened beams have shown the significant enhancement that can be obtained under service or ultimate conditions by the application of an FRP laminate to the tension face of an element. Nevertheless, researchers have highlighted types of brittle failure involving the laminate peeling-off that can limit these gains. As a result of the FRP application, the mode of failure of a flexural element may change from ductile to brittle.

The debonding mechanism is driven by stress concentration at the laminate end or in the vicinity of existing cracks, and is generally initiated from within the concrete substrate between the externally bonded laminates and the internal reinforcement. Therefore, the reliability of the FRP reinforcement depends mainly on a proper stress transfer from concrete to laminate through the interface.

Since a premature failure prevents the strengthened element from reaching its theoretical ultimate capacity and also implies a reduction of ductility, a methodology for design purposes to predict the peeling failure load should be developed. A number of investigators have attempted to work in this direction. Most of the existing theoretical work has been focused on the stress behavior at the plate end. However, experimental studies have shown that the premature plate debonding may also start at the opening of a flexural or shear crack. Therefore, there is a need to improve the knowledge of the peeling process in both locations to be able to predict premature failures.

1.2.2. Objectives

The aim of this research is to contribute to the knowledge of reinforced concrete structures that are externally strengthened by FRP laminate bonding, focusing especially on the stress transfer from laminate to concrete through the interface, which is the main key in its correct performance.

To achieve the above general aim, the following specific objectives will be pursued.

1) To study the feasibility of strengthening concrete structures with the use of composite bonded laminates by means of an experimental program on beams externally reinforced by CFRP laminates.
2) To critically review the existing theoretical methods developed to prevent premature failures related to laminate debonding.
3) To evaluate the performance of these methods by contrasting their prediction outcomes on the failure load to the experimental values obtained from published experimental programs.
4) To understand the stress transfer in a pure shear specimen where only shear stresses are acting on the interface. To obtain the distribution of shear stresses

with increasing values of the external load by applying equilibrium and compatibility.
5) To extend the formulae to a general case of a beam subjected to transverse loads, where laminate peeling-off may suddenly appear either near flexural or shear cracks, or at the laminate end.
6) After achieving the previous objectives, the main goal will be the proposal of a simple and efficient method for design or verification purposes in order to prevent the premature and brittle peeling failure mode.

1.3. Contents of thesis

To achieve the objectives described above, the thesis is divided into six chapters. In Chapter 2, a historical overview of the published work on externally strengthening concrete structures by plate bonding is conducted. This chapter is divided into two sections respectively associated to an experimental or theoretical line of research.

Presented in the first section is a review of the experimental programs regarding externally bonded structures since the introduction of composites in this field. Then, based on this review, a classification of the observed failure modes is given. Some anchorage devices employed to avoid premature failure modes are described. Through the experimental review, tests on beams under three-or-four point bending as well as single and double shear tests have been compiled into two databases which are presented in this chapter. However, both databases are described in more detail in Appendix A and B respectively. At the end of this section, the results from an experimental program on beams externally strengthened by pultruded laminates which was performed by the author at the Structural Technology Laboratory of the Technical University of Catalonia (UPC) are summarized. Even so, a more extensive discussion can be found in Appendix C.

In relation to the theoretical line of research, an overview of the existing models to prevent premature failures is presented. Models have been classified into four groups according to their basis: truss models, linear elastic models, shear capacity based models, and concrete tooth models. Their performance is evaluated through statistical analysis by using the bending test database.

The application of Non-Linear Fracture Mechanics theory to describe the interface behavior and its premature failure is presented in Chapter 3. By assuming a bond-slip relationship and applying equilibrium, the stress transfer between concrete and laminate is obtained in a pure shear case. The suitability of the developed model is studied by comparing the theoretical maximum transferred force to the experimental value obtained in the pure shear tests compiled in the database.

The formulae presented in Chapter 3 are extended to a general case of a beam subjected to transverse loads in Chapter 4. The distribution of shear stresses is obtained between two cracks and at the laminate end. Some examples of application are also given.

Afterwards, a simple procedure for design or verification purposes to obtain the peeling failure load is described in Chapter 5. This proposal is based on the calculation of the maximum shear force that can be reached before a peeling failure occurs. Since this premature failure can initiate near cracks or at the laminate end, the proposal should avoid peeling failure at both locations. The maximum shear force that prevents peeling near cracks is obtained by assuming that debonding starts when the transferred force between concrete and laminate along the crack distance reaches its maximum value. Under these circumstances, the laminate end debonding should be checked. To prevent peeling failure at the laminate end, the transferred force between this location and the nearest crack should be lower than the theoretical maximum value. In case this condition is not accomplished, the maximum shear force before peeling occurs is readjusted. The suitability of this new methodology is evaluated by comparing the predicted peeling failure load to the experimental value given by those beams of the database that failed by laminate peeling-off.

Finally, conclusions based on the previous work, together with suggestions for further research, are drawn and summarized in Chapter 6.

In addition, Appendix D gives further information about the assumptions and contour conditions considered in the derivation of the interfacial shear stresses in a pure shear specimen and in a beam element subjected to transverse loads.

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Other PhD theses that were developed at the Construction Engineering Department are also related to strengthening structures by bonding composite materials. A list of them is given below:

Salaverría, J. (2002). “Utilización de nuevos materiales para la reparación y refuerzo de puentes”.

Landa, G. (2002). “Estudio experimental sobre el refuerzo a cortante de estructuras de hormigón mediante materiales compuestos”.

Aire, C. (2002). “Estudio experimental del hormigón confinado sometido a compresión”.

Alarcón, A. (2002). “Estudio teórico-experimental sobre la reparación y refuerzo de puentes de dovelas con fibras de carbono”.