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Review

Research progress on the flexural behaviour of externally bonded RC beams

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ABSTRACT

The flexural behaviour of strengthened reinforced concrete (RC) beams is more complicated compared to the normal beams due to the different bond conditions and properties of the externally bonded material. A significant number of research studies have been reported on the use of different types of material for flexural strengthening of RC beams using the external bonding (EB) technique. Although most research has focused on the conventional strengthening materials, namely, steel plates, FRP and ferrocement; unconventional materials, such as sprayed FRP and cement-based composites, have shown that they also have a significant effect on the behaviour of bonded beams. This paper presents a comprehensive state-of-the-art review of the different materials used for strengthening RC beams using the EB technique and their evaluation criteria. The behaviour of the strengthened beams is discussed in terms of load carrying capacity, stiffness under service loads, and ductility and failure modes. In addition, the effect of elevated temperatures on the externally bonded materials is also discussed. The critical review of the existing data can help for a better utilization and usage of the different materials for strengthening projects, which contributes significantly to the current efforts of developing optimum and feasible strengthening systems.

1. Introduction

Existing reinforced concrete (RC) structures are in need of upgrading and retrofitting for the following reasons: the excessive applied load resulting from the increase in traffic volume, some original design or detailing error, or the corrosion of internal steel reinforcement. The investigation of the behaviour of strengthened RC structures began with the increase in the number of strengthening applications throughout the world. In the last three decades, a number of strengthening and rehabilitation techniques of a variety of structural elements have been proposed and studied. Concrete columns are usually strengthened by applying lateral confinement, whereas RC beams and slabs are strengthened in flexure by attaching reinforcement to their soffits. The two main techniques for the flexural strengthening of concrete beams are the external bonding (EB) and near surface mounting

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(NSM). The reinforcement is applied in the EB technique by attaching the strengthening materials to the beam tension face using strong adhesive and/or mechanical fastening. The NSM technique involves embedding the strengthening materials with adhesive inside grooves or pre-cuts made in the concrete cover. The main aim of using any strengthening system is to achieve an improvement in the beam stiffness and strength with satisfactory ductile behaviour. However, the performance of externally bonded beams is influenced by a number of factors, such as the bond strength between the material and concrete, and the properties of the material itself [1,2].

The selection criteria of strengthening materials depend on certain factors, such as the durability of the material, ease of handling on site, and cost-effectiveness. However, research on the development of optimum strengthening materials is still needed. Therefore, a proper understanding is required for the properties of the different materials and the performance of strengthened beams. A number of state-of-the-art reviews on the use of different materials for strengthening and retrofitting have been documented [3–11]. The different aspects of the behaviour of beams bonded with steel plates were discussed by Raoof and Zhang [3]. Meier [4], Bakis et al. [5], and Zaman et al. [6] presented the potential for using fibre reinforced polymer (FRP) for strengthening and discussed its use for different strengthening applications. Pendhari et al. [7] and Bank [8] also examined the FRP strengthening on the behaviour of the different structural elements. The recent review by Chin et al. [9] focussed on the use of FRP for the external strengthening using FRP for beams with square and circular openings. Furthermore, the use of ferrocement for the construction and repair of RC members has been reviewed by Sakthivel and Jagannathan [10], and Paramasivam [11]. However, the reported reviews only focussed on one type of strengthening material. In addition, a large number of new materials other than the commonly used materials, namely, steel, FRP and ferrocement have recently been proposed for the external strengthening of RC beams. Thus, a critical review that addresses the new developments in the strengthening materials and compares all the materials used for the EB technique is needed. Therefore, the aim of this research work is to briefly discuss the materials that have been used for the external strengthening of RC beams over the last three decades and provide a critical comparison based on the different aspects of behaviour of the bonded beams. The evaluation of the effectiveness of the strengthening materials can help researchers and engineers for further development of better materials and techniques for strengthening and retrofitting. In the context of this research, the strengthening materials are divided into two main groups. The first group contains the three most common materials that have been early adopted and investigated for strengthening. These materials are the steel, FRP and ferrocement, and are termed ''conventional'' strengthening materials. The second group contains the other materials that have been recently introduced to the strengthening field, such as, reinforced-polymeric mortar composites and cement-based composite materials. These materials are termed ''unconventional'' strengthening materials. The different aspects of the behaviour of beams bonded with the conventional materials are examined and compared with respect to carrying capacity, serviceability and ductility. In addition, the reported test results available in the literature for the beams bonded with the unconventional materials are highlighted and compared with the conventional materials. Moreover, the different factors that affect the performance of beams bonded using the EB technique, such as, strengthening configuration, external mechanical anchorage and elevated temperature are presented and discussed.

2. Development of strengthening materials

The attachment of the repair material to the soffit of beams is considered as the earliest and most basic method for upgrading and retrofitting. As shown in Fig. 1, a number of materials have been adopted for external strengthening compared to the NSM technique.

2.1. *Conventional materials*

2.1.1. *Steel*

The use of steel plates for the flexural strengthening of RC structures is one of the earliest methods adopted in the last century in the structural upgrading field. The use of steel plates began in the 1960s and has been adopted in many countries thereafter due to the fast and simple process, and the fact that it can provide an economical solution compared to the demolition of the structure [12]. The steel used for external strengthening is in the form of mild steel plates bonded to the soffit of the concrete beams using strong adhesive and/or mechanical connectors (bolts). However, one of the main problems observed later in steel plates is the poor corrosion resistance. Exposure tests performed by Raithby [13] and MacDonald and Calder [14] indicated that a considerable amount of corrosion occurs at the steel/epoxy interface, which results in a decrease in strength and local debonding. In addition, steel is a relatively heavy material with a density of about 7800 kg/m^3 [15]. Hence, the difficulty in handling steel plates on site due to the heavy weight is another challenge for the use of steel as a strengthening material.

2.1.2. *FRP*

Considerable attention has been given in recent years to the FRP materials due to their advantages over steel plates, such as good durability properties, ease of transportation and handling on site and high strength to weight ratio. The density of FRP is typically between 1200 and 2100 kg/m^3 [16]. This means that the FRP is about 85% to 73% lighter than the steel, which leads to less equipment and a smaller workforce on site. The investigation of the FRP for flexural strengthening started in the mid-1980s. The most common types of FRP are glass (GFRP), aramid (AFRP) and carbon (CFRP) [17]. However, the CFRP seems to be preferred for strengthening due to its higher compressive strength and stiffness compared to the other two types [18]. ACI 440.2R-08 [16] specified three different forms of FRP used for external strengthening, namely, wet layup, prepreg and procured. The use of the three different forms of FRP depends on the type of application on the concrete structures and their transportation and handling on site. In addition, the different types of FRP can be combined and used