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Serviceability and moment redistribution of continuous concrete members reinforced with hybrid steel-BFRP bars

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HIGHLIGHTS

- Continuous concrete specimens reinforced with BFRP or hybrid steel-BFRP were tested.
- Serviceability performance of the tested specimens was examined.
- Moment redistribution of the tested specimens was evaluated.

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ABSTRACT

Test results of 12 two-span concrete specimens internally-reinforced with basalt fiber-reinforced polymer (BFRP) or hybrid steel-BFRP bars are reported in this paper. Six specimens were designed to be over-reinforced whereas the remaining six specimens were under-reinforced. The specimens had different hogging-to-sagging reinforcement ratios. Specimens with hybrid steel-BFRP bars were designed in a way to have hogging-to-sagging nominal moment strengths similar to those of their counterpart specimens reinforced with BFRP bars only. Specimens reinforced with hybrid steel-BFRP bars exhibited less deflections and smaller crack widths at service load than those of their counterparts with BFRP bars only. The hybrid-reinforced specimens were, however, able to undergo significant deformations prior to failure comparable to those exhibited by their counterparts reinforced with BFRP bars only. The behaviour of the specimens reinforced with BFRP bars only deviated from the elastic response. This deviation tended to increase by decreasing the hogging-to-sagging reinforcement ratio. Specimens reinforced with hybrid steel-BFRP bars exhibited less deviation from the elastic response compared with that of their counterparts reinforced with BFRP bars only.

1. Introduction

Non-metallic fiber-reinforced polymer (FRP) bars have a great potential to replace conventional steel reinforcement and eliminate corrosion problems in reinforced concrete structures. FRP-reinforced concrete elements fail either by concrete crushing or rupture of the FRP bars. The latter mode of failure leads to a sudden release of energy and immediate loss of load capacity. As such, it is considered more brittle than the former mode of failure [1–5]. Therefore, the ACI 440.1R-15 [5] recommends a minimum FRP reinforcement ratio of $\rho_f = 1.4\rho_{fbal}$, where ρ_{fbal} is the balanced reinforcement ratio, to ensure that concrete crushing would take place prior to the rupture of the FRP at ultimate load. Concrete elements internally-reinforced with FRP bars exhibit larger deflections and greater crack widths than those reinforced with conventional steel bars [1–5]. Therefore, some researchers recommended the use of hybrid reinforcement (*i.e.* a combination of FRP and steel reinforcing bars) to improve the serviceability of FRP-reinforced concrete elements [6–11].

Few investigations focused on studying the nonlinear behaviour of continuous concrete elements internally-reinforced with FRP bars [12–15]. These studies showed that moment redistribution could occur in continuous beams reinforced with adequate FRP reinforcement in the sagging regions without compromising the beam serviceability. Nevertheless, due to the lack of experimental evidence, most design guidelines and standards do not allow moment redistribution in continuous concrete structures internally-reinforced with FRP bars [5,16,17].

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BFRP bars have recently emerged as a promising addition to the existing fiber-reinforced polymer family. BFRP bars have become the focus of several studies devoted to determining their short- and long-term properties [18–21]. Few studies, however, focused on the feasibility of using such bars as internal reinforcement for concrete structures [11,22]. More research is, therefore, needed to advance development of guidelines and standards on design of concrete structures using BFRP bars.

This research aims to examine the nonlinear behaviour of continuous concrete elements internally-reinforced with BFRP bars only or a combination of steel and BFRP bars. The serviceability and moment redistribution of continuous concrete specimens reinforced with hybrid steel-BFRP bars are studied and compared with those of similar specimens reinforced with BFRP bars only. Results of the present study are anticipated to assist researchers and design practitioners to better understand the nonlinear behaviour of continuous concrete structures partially or fully reinforced with BFRP bars.

2. Experimental program

The experimental study comprised testing of 12 two-span concrete specimens. The test matrix is given in Table 1. Specimens of groups [A] and [B] were reinforced with BFRP bars only whereas those of groups [C] and [D] were reinforced with hybrid steel and BFRP bars. Six specimens, groups [A] and [C], were over-reinforced and six specimens, groups [B] and [D], were under-reinforced. The sagging reinforcement ratio was $3.2\rho_{fbal}$ for specimens of group [A] and $0.95\rho_{fbal}$ for those of group [B]. Three hogging-to-sagging reinforcement ratios, namely 0.5, 0.75, and 1, were adopted in specimens of groups [A] and [B]. These ratios corresponded to hogging-to-sagging nominal moment strength ratios of 0.75, 0.85, and 1 for specimens of group [A] and 0.5, 0.75, and 1 for specimens of group [B], respectively, as given in Table 1. The nominal moment strengths of the sagging and hogging sections in the hybrid-reinforced specimens of groups [C] and [D] were almost equal to those of their counterparts of groups [A] and [B], respectively, reinforced with BFRP bars only.

2.1. Materials

The cylinder and cube compressive strengths of the concrete used in this study were 43 and 58 MPa, respectively, whereas the splitting tensile strength was 4.0 MPa. Sand-coated BFRP bars with nominal diameters of 8, 10, and 12 mm, were used. Three replicate BFRP specimens from each diameter were tested under uniaxial tension forces up to failure. The 8, 10, and 12 mm bars had ultimate tensile strengths of 1235, 1227, and 1230 MPa, and moduli of elasticity of 48, 46, and 46 GPa, respectively. The steel reinforcement consisted of 8 and 12 mm diameter deformed bars. Their yield strengths were 554 and 584 MPa, and their ultimate strengths were 630 and 661 MPa, respectively.

2.2. Specimens

Test specimens were 500 mm wide, 200 mm deep, and 5000 mm long. They had two equal spans, each having a length of 2400 mm. The tested specimens would represent continuous wide beams in a band beam structural system commonly used in office buildings and parking structures. Fig. 1(a) shows a schematic of a typical test specimen whereas photos of steel cages are shown in Fig. 1(b). The shear reinforcement is not shown for clarity in Fig. 1(a) for clarity. The hogging reinforcement in all specimens had a length of 1600 mm and placed symmetrically about the central support. The hogging reinforcement extended inside each span for a distance of L/3, where L is the span length. The sagging reinforcing bars were 2395 mm long. They were placed at a distance 15 mm away from the edge of the specimen and 90 mm away from the middle support. The specimens were heavily reinforced in shear to ensure that a flexural mode of failure would dominate. The shear reinforcement in all specimens consisted of 8 mm diameter double-leg deformed steel stirrups spaced at 50 mm.

2.3. Test set-up and loading procedure

All specimens were tested to failure under displacement control at a rate of 1.5 mm/min. The specimens were subjected to two point loads; each was located at a distance of 0.4L from the middle support. The load was applied using a 500kN-MTS actuator placed at the midpoint of the specimen. A rigid spreader steel beam was used to distribute the load equally to the two point loads. A load cell was placed between the actuator and the spreader beam to record the total applied load. Another load cell was placed between the middle support and the soffit of the specimen to record the middle support reactions. Two linear variable differential transducers (LVDTs) were used to record the deflections under the load points. All specimens were initially loaded until the initiation of the first visible flexural cracks in both sagging and hogging regions. The specimens were then unloaded to allow for installation of crack clip transducers at the extreme tension fiber of concrete in the sagging and hogging regions at locations of the first visible flexural cracks. Following the installation of crack clip transducers, the specimens were loaded back to failure.

Table 1
Test matrix.

Group		Specimen	BFRP reinforcement		Steel reinforcement		Hogging-to-sagging nominal moment strength ratio
			Hogging	Sagging	Hogging	Sagging	
Specimens reinforced with BFRP bars only	[A]	A1	1Φ10 + 2Φ12	2Φ10 + 4Φ12	–	–	0.75
		A2	2Φ8 + 3Φ12	2Φ10 + 4Φ12	–	–	0.85
		A3	2Φ10 + 4Φ12	2Φ10 + 4Φ12	–	–	1.00
	[B]	B1	2Φ8	1Φ8 + 2Φ10	–	–	0.50
		B2	3Φ8	1Φ8 + 2Φ10	–	–	0.75
		B3	1Φ8 + 2Φ10	1Φ8 + 2Φ10	–	–	1.00
Specimens reinforced with hybrid steel and BFRP bars	[C]	C1	2Φ8 + 1Φ10	1Φ10 + 3Φ12	2Φ12	2Φ12	0.75
		C2	2Φ8 + 2Φ10	1Φ10 + 3Φ12	2Φ12	2Φ12	0.85
		C3	1Φ10 + 3Φ12	1Φ10 + 3Φ12	2Φ12	2Φ12	1.00
	[D]	D1	1Φ8	3Φ8	2Φ8	2Φ8	0.50
		D2	2Φ8	3Φ8	2Φ8	2Φ8	0.75
		D3	3Φ8	3Φ8	2Φ8	2Φ8	1.00