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Strength and ductility of simple supported R/C beams retrofitted with steel plates of different width-to-thickness ratios

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A B S T R A C T

The concept of strengthening reinforced concrete beams using epoxy-bonded steel plates (EBSP) is a well-known solution in structural engineering, however, there is little information about the effect of the width-to-thickness ratio of steel plates on the behaviour of steel–concrete composite beams. This paper presents an experimental study of the flexural behaviour of under-reinforced concrete beams, strengthened in flexure by externally-bonded steel plates (EBSP) of varying width-to-thickness ratios. A total of 23 reinforced concrete beams were tested; 6 beams in Series 1 tests and 17 beams in Series 2 tests. One beam in Series 1 tests and two beams in Series 2 tests were regarded as control specimens, whilst the remaining beams were strengthened with steel plates of different width-to-thickness ratios. In each group, the width of the bonded steel plate varied from 75 mm to 175 mm, in increments of 25 mm. The beams were tested as simply supported, under two-point static loadings until failure. From the experimental results, it was observed that the externally bonded steel plates led to substantial increase in flexural stiffness, which resulted in an increase in the capacity and cracking load of the strengthened beams and a decrease in vertical deflections and crack-widths, compared to the control beams. It was also found that the width-to-thickness ratio of steel plates as low as 12.5 can promote flexural yielding and extensive ductility in strengthened beams.

1. Introduction

The need for strengthening beam elements in reinforced concrete structures arises, when the capacity of an existing structure is no longer adequate to resist the current design loads or when the structure is now required to resist larger ultimate loads. The former is usually caused by design errors, inadequate detailing, construction faults, usage of inferior materials during construction and loss of capacity due to corrosion or other types of degradation caused by aging, or a combination of these factors. Although there are several methods for strengthening reinforced concrete beams, strengthening of reinforced concrete beams using epoxy-bonded mild steel plates on the tension face has been proven to be the most effective, efficient, economical and convenient technique to enhance the flexural and shear performance of reinforced concrete beams under service and ultimate loads [1–17]. Steel plates are relatively cheaper and readily available, has uniform material properties (isotropic), high ductility and high fatigue strength, can be secured easily whilst the structure is in use [5], does not significantly change the overall dimensions of the structure, and can be secured without causing any damage to the structure [8]. This technique has been applied successfully to strengthen reinforced concrete structures such as buildings and bridges in various parts of the world, including South Africa, France, Switzerland, Japan, Poland, Belgium and United Kingdom [4]. Although, fibre reinforced polymers (FRP) plates are preferred in other parts of the world, because of their superior strength-to-weight ratio and corrosion resistance, they are very expensive and not readily available in South Africa, and the rest of Africa. Excluding import costs, the cost of FRP can be 10 times as much as that of steel plates [18,19]. In addition, the use of FRP poses the increased possibility of brittle failure modes.

The technique was pioneered by Fleming and King in South Africa [1] and L'Hermite and Bresson in France [2], and since then many studies have been conducted to fully understand the structural behaviour of reinforced concrete beams strengthened by externally bonded steel plate on their soffit [3–17]. However, there is limited work about the effect of the width-to-thickness ratio of steel plates on the behaviour of steel-concrete composite beams. L'Hermite and Bresson [2], Macdonald [3], Bloxham [4], Jones et al. [6], Huovinen [13], Neelamegan et al. [15] and Oh et al. [16] recognised that the width-to-thickness ratio of steel plates could have an influence on the premature failure of strengthened beams. L'Hermite and Bresson [2] tested strengthened beams with mild steel plates of width-to-thickness ratio of 24 only, and

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Table 1
Material properties of reinforcement bars, steel plates and concrete.

Series	Specimen	f_y (MPa)	ε_y (%)	f_u (MPa)	ε_u (%)	E_s (GPa)	f_{cu} (MPa)	f_{ck} (MPa)
Series 1	Y10-1	442.77	0.417	648.59	16.300	203.07	30.0	24.0
	Y10-2	448.95	0.419	652.64	16.200	204.07		
	Y10-3	442.90	0.448	649.92	15.800	198.34		
	Average	444.88	0.428	650.38	16.100	201.83		
	SP6-1	344.59	0.189	421.28	18.700	204.28		
	SP6-2	353.17	0.153	423.57	19.100	202.50		
	Average	348.88	0.171	422.43	18.900	203.39		
Series 2	R6-1	380.95	0.425	421.46	13.311	202.30	31.5	25.5
	R6-2	380.60	0.406	428.60	16.055	200.80		
	Average	380.78	0.416	425.03	14.683	201.50		
	Y8-1	353.64	0.431	386.14	3.964	201.00		
	Y8-2	356.32	0.418	387.83	5.515	200.00		
	Average	354.98	0.425	386.98	4.740	200.50		
	Y12-1	442.80	0.468	596.97	20.244	200.30		
	Y12-2	450.38	0.437	596.00	17.828	200.50		
	Average	446.59	0.453	596.53	19.036	200.40		
	SP4-1	421.34	0.335	536.73	15.006	200.90		
	SP4-2	421.44	0.380	541.11	14.946	200.10		
	SP4-3	421.48	0.385	537.21	14.940	205.20		
	Average	421.42	0.367	538.35	14.964	202.40		
	SP6-1	398.63	0.418	529.45	18.031	201.40		
	SP6-2	397.52	0.407	528.10	18.943	204.00		
	SP6-3	398.68	0.408	529.31	18.930	203.50		
	Average	398.28	0.411	528.95	18.635	203.00		
	SP8-1	326.39	0.378	426.55	17.689	201.80		
	SP8-2	326.54	0.327	429.72	18.619	200.00		
	SP8-3	321.93	0.369	426.84	18.381	204.00		
	Average	324.95	0.358	427.70	18.229	201.90		

suggested that, had the width-to-thickness (w/t) ratio of the steel plate been larger, full composite action might have been possible. Several years after L'Hermite and Bresson's work, Macdonald [3] concluded that the reinforced concrete beams should be strengthened with steel plate having width-to-thickness ratio of not less than 22 in order to obtain composite action.

To ensure that full composite action is achieved, Bloxham [4] suggested that the width-to-thickness ratio of the steel plate should not be less than 50 and the neutral axis depth should not be more than 0.4 times the effective depth. Jones et al. [6] tested one (1) control beam, and four (4) under-reinforced concrete beams with an adhesive thickness of 3 mm, and compressive strength, tensile strength and modulus of elasticity of 44 MPa, 5.3 MPa, and 6 GPa, respectively. From this work, it can be concluded that the width-to-thickness ratio of the steel plates should range from 26.67 to 53.33 if full composite action is to be accomplished. Huovinen [13] investigated the bond strength of glued steel plates of 6 strengthened beams, with two types of adhesive resin (Epoxy BI-R glue and Concressive 1380 glue) for each steel plate, and concluded that the width-to-thickness ratio of plates should not be less than 20 for flexural yielding of the strengthened beams to occur. In a wider investigation, Neelamegam et al. [15] tested nine (9) strengthened beams with varying length bonded plates of 800–2200 mm long. The strengthened beams with steel plates of at least 43.5 width-to-thickness ratio maintained composite action until failure and failed by flexural yielding. Lastly, in an investigation performed by Oh et al. [15], beams with width-to-thickness ratios of 37.5, 50 and 70, and shear span –to–depth (a_v/d) of 4.77 failed by yielding of the external plate followed by plate separation.

The brief review above clearly shows that there is a lack of comprehensive information about the effect of the width-to-thickness ratio of steel plates on composite beams. Added to this, there is huge inconsistency about the width-to-thickness ratio of the steel plate that should be used to promote yielding and ductility of the composite beams. The objectives of this study are to determine the effect of the width-to-thickness ratio of steel plates on the flexural capacity, deflections and flexural stiffness of beams, and to evaluate the width-to-thickness ratio of steel plates that encourage yielding of the composite beams. In addition, the experimental results are compared with the theoretical results predicted using EN 1992-1-1 [20].

2. Material properties

A detailed evaluation of the capacity of strengthened beams depends heavily on the reliability of the properties of the materials used. This section describes the tensile and compressive test procedures to determine the material properties of the reinforcement bars, steel plates and concrete cubes.

2.1. Reinforcement bars and steel plates

The material properties of the reinforcement bars (6 mm, and 8 mm and 12 mm) and steel plates (4 mm, 6 mm and 8 mm) were established from the tensile coupon tests. Mild steel was used for the 6 mm shear links (R) in Series 2, and high yield strength (Y) deformed steel was used for the main reinforcement in all beams and as well as the shear links in Series 1. Reinforcement diameter bars and steel plates (SP) were cut using a metal cutter, and the steel plates were prepared into coupons using a Topaz steel mill machine, in accordance with EN ISO 6892-1 [21]. The reinforcement bars were cut to a length of 250 mm, and each bar was tested in their original diameters of 6 mm, 8 mm and 12 mm.

Before testing, the specimens were firmly gripped at both ends to prevent slippage. After all the necessary preparations were done, the specimens were tested using a 100 kN capacity displacement controlled Instron 1195 tensile testing machine. A calibrated extensometer, with a gauge length of 50 mm, was used to measure the axial elongation of the specimens during tensile testing. The specimens were pulled at a rate of 3 mm per minute and the stress-strain relationship for each steel coupon was derived from the load-strain relationship, using the original cross-sectional area and gauge length of 50 mm. The 0.2% proof yield stress (f_y), yield strain (ε_y), ultimate stress (f_u), ultimate strain (ε_u) and the Young's Modulus of Elasticity (E_s) were determined from the stress-