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Experimental Response of T-Beams with Exposed Reinforcement under Static Point-Loads

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Abstract - Recent catastrophic events showed the critical need for assessing the performance of existing reinforced concrete infrastructure, whether subjected to aging or made by poorly designed structural elements, under both service and extreme loading conditions. To assess the effects of exposed longitudinal reinforcement on reinforced concrete beams, usually found in aging bridges, a series of point-load tests on beams with a T-shaped cross section and exposed reinforcement are performed. Flexural strength and stiffness reduction are estimated as a function of the exposed length of the reinforcement. Results show that reinforcement exposure leads to a reduction in strength and stiffness of the beam, and the longer the length of the exposure, the larger is the measured reduction in stiffness.

Keywords**:** Exposed reinforcement; Unbonded reinforcement; T-beams; Aging infrastructure

1. Introduction

Reinforced concrete (RC) is the most widely used material in the construction industry due to its versatility in construction and durability, provided proper care and maintenance are planned and executed. Aging of RC infrastructure is of significant concern given the threat to human life and the large amount of public money that is spent on rehabilitation [1]. Two main tragic events (e.g., the Mexico City Metro overpass collapse in May or the Miami Surfside Condominium collapse in June of last year) reminded structural engineers about the critical need for the assessment of aging infrastructure subjected to both service and extreme loading conditions. Loss of concrete cover caused by corrosion or due to patch repairs inhibits the bond between concrete and reinforcement and may affect the overall structural safety. In these compromised conditions, code equations [2] for ultimate bending capacity may overpredict the actual strength, because the assumptions on strain compatibility are not satisfied [3]. Characterization of flexural strength and stiffness degradation due to aging is critically needed. To this end, this study describes a series of static tests on beams with a T cross-section aimed at assessing the effect of reinforcement exposure due to aging on beam strength and stiffness.

2. State of the Art

Several researchers have performed experimental tests to understand the behaviour of reinforced concrete beams with exposed tensile reinforcement, see Table 1. Most of the past studies focused on rectangular cross-section beams. Small scale simply supported beams with span lengths of 3 m or less were tested under different static loading conditions. The testing results show that the loss of bond between concrete and reinforcement significantly modifies the type of response of RC beams under ordinary loading conditions, transitioning from pure flexural to hybrid tied-arch and flexural response. This also results in reduced flexural strengths.

Table 1. Test specimens and results from the literature.

Ref.	Cross section	Dimensions (mm)	ρ (%)	Load	Span (m)	Length of exposure L_{ex} (%)	Number of tested specimens	Measured strength reduction
[4]	R	127 x 254	0.95	1♠	2.9	63%	40	21%
[5]	R	75 x 130	1.8	1	1..7	23.5%	36	35% (No top steel)
[3]	R	Dimensions vary. Rectangular cross-sections: 150-233 x 230-410	1.5 0.5	2	2.7-3	90%	19	50% (ρ=1.5%) 0% (ρ=0.5%)
[6]	R	75 x 130	1.6	1	1.76	22.7%	44	50% (No top steel)
	R	150 x 300	1.1-1.4 & 1.1	1	3	30%	88	41% (No top steel) & 31% (with top steel and links)
			1.1	2		30%		48% (No top steel)
[7]	R	120 x 200	1.1	2	1.8	50%	2	10%
[8]	R	100 x 150	1.7	2	1.5	90%	5	35%
[9], [10]	T	Flange 800 x 90; Web 200 x 310	0.37	1×	4	86.5%	6	29%
[11]	R	100 x 150	2.5	1	1.9	85.4% & 51.4%	7	55% (exposure at midspan) & 36% (exposure near the supports)
Cross section: R= rectangular cross section and T = T=shaped cross section Load: 1: One-point load; 2: Two-point load; 4: Four-point load ♠: Load applied outside the exposed zone ×: Uniform load also applied								

The main conclusions from the literature are reported below:

- The amount of beam reinforcement ratio influences strength reduction. In general, the larger the amount of reinforcement the larger is the reduction in strength [3] [6]. For simply supported beams with rectangular cross-sections, subjected to one- or two-point load, reinforcement exposed at midspan and a minimum 1.5% reinforcing ratio, the strength reduction ranges between 35 and 55% when 85-90% of the span length of reinforcement is exposed [3] [8] [11]. A discrepancy can be noticed in test results on beams with similar load and exposure arrangements, but with lower reinforcing ratios (0.5% or smaller); some studies [3] showed almost no noticeable strength reductions, whereas other authors reported a strength reduction of approximately 30% (e.g. [10]). This inconsistency may be due to the different experimental setups. The length of exposed reinforcement directly affects strength reduction, as most of the studies show larger decrease in strength for longer lengths of exposed reinforcement [3] [4] [5] [6] [11].

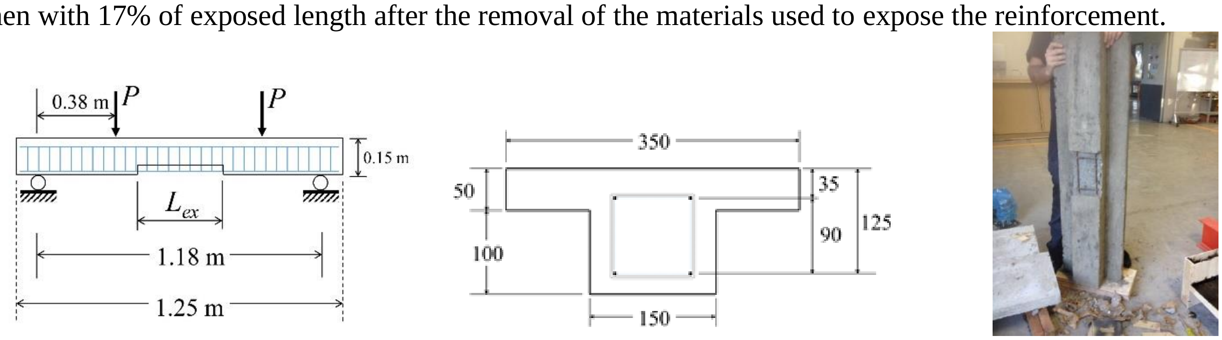
- The presence of top steel benefits the beam strength in exposed conditions. Tested beams with top steel resulted in about 10% stronger than similar beams without top reinforcement, even for longer lengths of reinforcement exposure [6].
- The location of the exposure seems to be an influencing factor as well: experimental results in beams with reinforcement exposed near one end showed that the more distant the location of the load is from the support, the greater the strength loss [5] [6].
- The ductility of tested beams is also negatively affected by the exposed reinforcement [3]. For cases when about 50% of the beam length is exposed, the ductility of the beam may reduce as much as 60% [7].
- Test results proved that the exposure of reinforcement causes a reduction in member stiffness, which alters the distribution of moments along the length of the element [12] [13].

3. Research significance

Whilst some research has been carried out on the response analysis of aging beams with exposed reinforcement, there have been few empirical investigations on T-beams with exposed reinforcement and focused only on strength capacity reduction. This study is aimed to explain and describe the behaviour of such beams by performing static tests and considering various lengths of exposure. The results of these tests showed strength and stiffness reduction in exposed T-beams and can be used for validating finite element analysis models considering RC degradation effects.

4. Experimental program

Six simply supported T-beams subjected to two-point loads at mid-thirds of the 1.18 m span were tested under static loading conditions. The test load setup is shown in Fig.1a and the cross section and reinforcement of the testing beams are presented in Fig.1b. The longitudinal steel reinforcement, designed according to the ACI [14], consisted of a pre-welded truss made of four 6 mm diameter ribbed bars and 4-mm plain stirrups spaced at 158 mm. One specimen was fully bonded and considered as the reference specimen in the interpretation of the results (length of exposure Lex = 0), whereas the rest of the specimens presented different lengths of reinforcement exposure, namely, 17% (Lex = 0.20 m), 34% (Lex= 0.40 m) and 68% (Lex = 0.80 m) of the beam span. Two identical specimens were reproduced and tested for the Lex = 0.20 m and Lex = 0.40 m lengths of exposure. Except for the reference specimen (Lex = 0), beams were cast with bars exposed over a segment of the span; plywood and cardboard panels were used to keep the steel reinforcement exposed. Fig. 1c shows a specimen with 17% of exposed length after the removal of the materials used to expose the reinforcement.

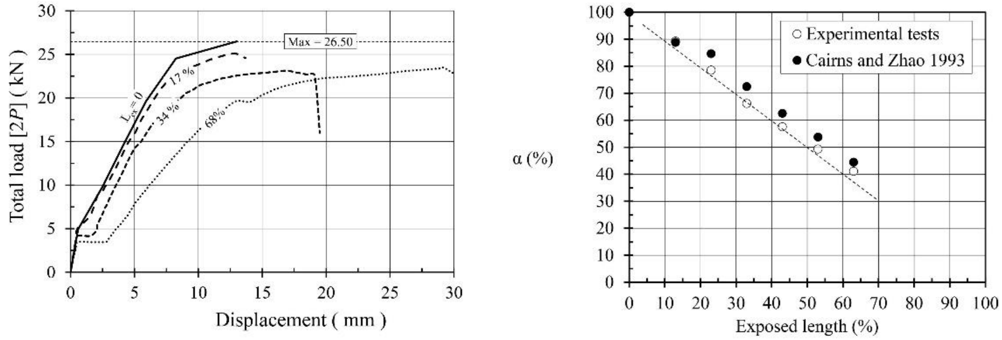


a) b) c)

Figure 1. a) T-beam testing setup, b) T-beam cross-section (dimensions in mm), and c) Picture of one of the two L_{ex} = 0.20 m specimens (with 17% of reinforcement exposure).

4. Test Results

During testing, load and deflection at midspan were measured. Fig. 2a shows the load-displacement curves of the testing specimens; the vertical axis represents the total applied load, 2P, and the horizontal axis the mid-span deflection. The curves for 17% (Lex = 0.20 m) and 34% (Lex = 0.80 m) of exposed length represent the average of the two identical specimens. These results agree with the load-deflection curves found in the literature [11] and they show that stiffness (slope) and strength (maximum value) are reduced by exposure of the reinforcement. It is also noted that reinforcement exposure increases the deflection at failure and this suggest also changes in ductility.



a) b)

Figure 2. Results of the tests. a) Load versus displacement curves and b) Experimental interpolated values of the coefficient of deterioration for stiffness versus exposed length of reinforcement. Comparison with experimental results estimated from Cairns and Zhao [3].

The results presented in Table 2 are the strength and stiffness reductions of the test specimens evaluated from the analysis of the curves shown in Fig.2a.

- ***Stiffness reduction***: A coefficient of deterioration for stiffness, α, is defined as the ratio between the stiffness of unbonded and fully bonded specimens. Its magnitude was computed from the load-displacement curves shown in Fig. 2a by taking the slope between two selected points: one at 10 kN and the other at 20 kN. The results are shown in Table 2. Values estimated by linear interpolation of the test results are compared with those from literature (Fig. 2b) having similar loading conditions [3]. The results show agreement with a linear trend on stiffness reduction. These data suggest that the change in exposed length is proportional and opposite to a reduction in stiffness, approximately in a one-to-one relationship, i.e., if the exposed length increases by 10%, the stiffness decreases by a comparable amount. It is envisaged that a change in stiffness for the case of statically indeterminate beams will affect internal moment distribution and increase the demand in other sections of the beam, posing an unquestionable hazard to the safety of unsound infrastructure.
- ***Strength reduction***: To investigate the influence of the length of exposed reinforcement on flexural strength, a coefficient of deterioration for strength, k_d, was introduced as the ratio between the load capacity of an unbonded specimen and the fully bonded reference specimen. Table 2 shows the calculated values. For short exposure lengths (17%, Lex = 0.20 m), the ultimate moment capacity is almost unaffected. However, when the length of the exposed reinforcement is approximately equal to the constant moment region of the beam or it extends beyond this point, the ultimate moment capacity is decreased by as much as 12% of the original capacity.

Table 2. Test results.

Specimen	**L_{ex} (%)**	**Max. Load, Pmax (kN)**	α	k_d
Reference	0	13.2	1.00	1.00
T1	17	12.5	0.86	0.95
T2	34	11.6	0.65	0.88
T3	68	11.7	0.37	0.88

5. Conclusions

The performance assessment of aging RC infrastructure is critical to understanding its safety. To describe how strength and stiffness of aging RC beams (typically found in bridges) are altered, a series of tests were performed. This study analyses the effect of reinforcement exposure on simply supported T-beams subjected to two-point loads. Within the scope of the study, the following conclusions are reached:

1. A reduction in stiffness and strength is observed. The magnitude of the reduction depends on the length of exposed reinforcement.
2. For the case of short lengths of reinforcement exposure, 17% of the beam length, the strength is almost unaffected.
3. In contrast, the stiffness is significantly reduced. The reduction in stiffness is inversely proportional to the exposure length.
4. The change in stiffness causes internal moment redistribution in statically indeterminate beams and hence the demand in sound sections of the beam may be critically increased beyond their design capacity. This may pose a significant hazard to the safety and reliability of such structures.

Acknowledgements

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