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Crack Formation in Bending Composite Elements

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Summary

The paper examines behaviour of composite structures, i. e. bending reinforced concrete elements, armoured externally under short - term static loadings the influence of external reinforcement and its anchorage towards resistance of crack formation, rigidity and strength has been analysed.

On the basis of the test results the methods for calculation of strength, cracking and rigidity have been compared.

1. Introduction

At present external glued reinforcement is widely used in the world for practical restoration of serviceability condition of structures. Strips or sheets of steel, glass fiber, asbestos cement are glued to the concrete surface of structures. Sheets and strips can be readily adjusted to various cross - sectional shapes, permanent load and depth of the structures practically are not increased, the job is quite simple and speedy.

External bonded reinforcement and the layer of polymer glue reduce concentration of stress in the tension zone, increase ultimate extensibility and tension strength of concrete, increase resistance to cracking and stiffness of members.

Resistance to cracking stiffnes and carrying capacity of flexural members with external reinforcement depend substantially on reliability of bond between concrete and external reinforcement. In the care of inadequate anchorage of the external reinforcement a crack may appear along the joint and consequently effect of external reinforcement reduces. Therefore it is essential to ensure reliability of bond between reinforcement and surface of the structure to be strengthened.

The best anchorage of glued reinforcement is achieved when this reinforcement is extended behind the supports. It is complicated to do so in strengthening of flexural members in service and it leads to the use of additional anchorage by the means of special anchors. It is associated with supplementary work and material expenditure. Thus the problem of required length of extension of glued reinforcement behind the critical cross - section, i.e. determination of the development length is urgent.

This article deals with influence of external glued reinforcement on crackresistance and strength of normal sections of flexural members - beams.

2. Experimental investigations in members strengthened with glued external reinforcement

Behaviour of flexural members - strengthened with glued external reinforcement have been investigated in the department of reinforced concrete structures of Vilnius Gediminas technical university.

Four series of beams have been tested under short time static load. A series consisted of 2 beams. Beams tested were of 70×100 mm in cross - section and length of the beams was l=970 mm. The beams were made of normal weight concrete of cube strength $R_{15,m}$=41,5 MPa, reinforced with 2∅5 Bp I (reinforcement ratio μ_s=0,00696). In addition beams were reinforced with the following external glued reinforcement:

- non - metallic - 3 layer of glass fabric impregnated with epoxy resin paste (series S1 and S3);
- metallic - 0,72 mm thick steel strip of grade S_T 3 (series S2).

The external reinforcement of beams of series S3 were lapped over external ribs of the beams.

Diagrams of control beams S0 and those with glued external reinforcement S1, S2 and S3 are shown in Figure 1.

In beam tests moment of crack formation $M_{crc,obs}$, failure moment $M_{u,obs}$, distance between normal cracks and limit deformations of concrete in Tension zone were determined.

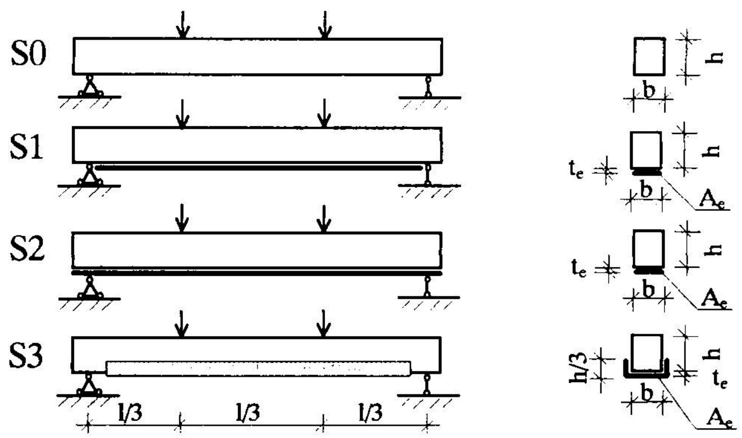

Fig. 1 Diagrams of reinforcing of beams with external glued reinforcement

The main characteristics of tested beams and the main test results are presented in Table1.

No of sample series	Cube strength of concrete in compre-ssion	External reinforcement				Test results			
		Type	Strength R_e, MPa	A_e, cm^2	$\varepsilon_{e,u} \times 10^5$	$M_{crc,obs}$ kNm	$\frac{M_{crc,obs,i}}{M_{crc,obs,o}}$	$M_{u,obs}$ kNm	$\frac{M_{u,obs,i}}{M_{u,obs,o}}$
S0		–	–	–		0,39	1	2,05	1
S1		glass fabric	55,6	2,775 2,625	1013	0,78	2	2,77	1,35
S2	41,5	metal strip	R_y= =287,7	0,504	400	1,3	3,33	2,21	1,08
S3		glass fabric	76,48	3,85 2,56	963	0,78	2	2,78	1,35

Table 1 The main characteristics of samples and test results

According to the test results (see Table 1) resistance to normal crack formation of beams strengthened with external non - metallic and metallic glued reinforcement increased by 2 and 3,33 times, respectively, in comparison with control beams.

Many fine cracks appeared in beams strengthened with external reinforcement. Their width a_{crc}=0,025 - 0,05 mm and average spacing l_{crc}=55 - 60 mm. Crack width in non - strengthened (control) beams was larger a_{crc}=0,15 mm and spacing was l_{crc}=85 mm.

Strength of cross - section increased 1,35 and 1,08 times respectively. Lower increase in strength of cross - sections of beams strengthened with metallic external reinforcement is due to the fact, that the metallic reinforcement was not fully exploited, because of inadequate strength of joint between reinforcement and concrete surfaces, reinforcement at support regions broke off and the bond between reinforcement and concrete surfaces was damaged.

3. Calculation of crack formation moment

Resistance of crack formation of flexural members with glued external reinforcement may increase due stress redistribution between strengthening structure and external reinforcement and also due to increased extensibility limit of concrete layers saturated with glue. Efficiency of exploitation of external reinforcement depends on deformability (yielding) of links, the function of which is performed by glue seam. Results of calculation of crack formation moment depend on the accuracy of assesment of yielding in glue seam. Quite a few number of methods for calculation of cracking formation moments proposed by various authors are known. Some of them are analysed and calculation results compared below.

Crack formation moment in reference [1] is recommended to calculate as follows:

$$M_{crc} = \frac{W_{pl} \cdot R_{br} \cdot k_p}{\left[1 - \frac{k_z \cdot z \cdot (z + r)}{\gamma \cdot E_b \cdot I_{red}}\right]}, \quad (1)$$

where: k_p is a coefficient to allow for tensile strength of concrete covered by polymer, $k_z \leq 1$ and it is coefficient to account for deformability (yielding) of the links; z is distance between external reinforcement and the centroid of the cross - section, r=distance between the centroid of the cross - section and the upper kern point.

In reference [2] a general method for calculation of crack formation bending moments of flexural reinforced concrete members with additional external non - metallic reinforcement is proposed. A triangular stress diagram in concrete under compression is recommended by the authors for the case when compressive stress in the extreme compressive layer of the cross - section does not exceed the limit of microcracking of concrete, and in the opposite case this diagram is assumed to be trapezium. Then M_{crc} is calculated as follows:

$$M_{crc} = \frac{c \cdot R_{bt}}{h_t}\left(I_{b,el} + \alpha_s' \cdot I_s' + \alpha_p' \cdot I_s' + \alpha_s \cdot I_s + \alpha_e \cdot I_e\right) + R_{bt}\left(S_{bt} + \varphi \cdot S_{b,pl}\right) + P \cdot e_n, \quad (2)$$

where: $c = \varepsilon_{bt,u}/\varepsilon_{bt,el}$, I_s', I_p', I_p, I_s are second moments of area of cross - sections of adequate compressive and tensile reinforcing bars; I_e, $I_{b,el}$ are such moments but of external reinforcement and of concrete compression zone the depth of which is equals to $x(1 - \eta)$; $S_{b,pl}$ - the first moment of area of concrete compression zone the depth of which is ηx, S_{bt}=the same but for tension zone in depth of h_t ; P=concrete precompression force; e_n =distance from the point of application of force P up to the neutral axis; h_t=tension zone depth in a section with crack; coefficient $\varphi = \sigma_{b,max}/R_{bt}$; α=reinforcement to concrete modular ratio

The method of calculation of crack formation moment proposed in reference [3] also allows for plastic deformations of concrete in tension. the following formula is proposed for cracking moment calculation:

$$M_{crc} = \frac{\varepsilon_{btu}}{h - x}\left[\frac{E_{bk} \cdot b \cdot x^3}{2 + n_\sigma} + E_s \cdot A_s (h_0 - x)^2 + E_e \cdot b_e \cdot t_e (h - x)^2 + E_{btu}' \cdot \frac{b(h - x)^3}{2 + f_t}\right], \quad (3)$$

where: ε_{btu} is ultimate deformations of extreme fibers of concrete in tension; E_{bk} is deformation modulus of glues; E_{btu}' is the secant deformation modulus of tension concrete at failure; $f_t = E_b / E_{btu}'$ and is characteristic of non - linear behaviour of tension concrete.

Sample code	Method 1 [1]	Method 2 [2]	Method 3 [3]	Method 4 [4]
	$\frac{M_{crc,obs}}{M_{crc,cal}}$	$\frac{M_{crc,obs}}{M_{crc,cal}}$	$\frac{M_{crc,obs}}{M_{crc,cal}}$	$\frac{M_{crc,obs}}{M_{crc,cal}}$
S1-1	0,948	1,413	1,03	1,50
S1-2	0,929	1,376	1,03	1,469
S2-1	1,363	1,854	0,755	1,903
S2-2	1,30	1,774	0,748	1,823
S3-1	0,91	1,340	0,941	1,432
S3-2	0,908	1,340	0,948	1,432
Bondarenko V.M. [3]	0,997	1,541	1,03	1,657
	1,144	1,10	1,05	1,937
	1,176	1,894	1,054	2,044
	0.858	1,217	1,08	1,315
	0,970	1,395	1,071	1,508
	1,060	1,538	1,084	1,666
Voronkov R. V [6]	0,993	0,719	-	1,33
	1,03	0,745	-	1,63
	1,00	0,730	-	1,33
	0,719	0,615	-	1,11
	1,09	0,759	-	1,01
	1,189	0,922	-	0,835
	1,2	0,931	-	0,835
*	0,832	1,214	-	1,324
*	0,894	1,39	-	1,518
*	1,142	1,649	-	1,795

* The beams tested at reinforced concrete department of VGTU

Table 2 Results of calculation of crack formation moments M_{crc}

Calculation methods	Number of samples	The mean value γ_m	Standard deviation S_γ	Coefficient of variation δ_γ	k_{min}, at $\beta=2$
1	22	1,03	0,158	0,153	1,4
2	22	1,248	0,388	0,311	2,12
3	12	0,985	0,118	0,12	1,34
4	22	1,47	0,33	0,225	1,24

Table 3 Results of statistical analysis of ratio $\gamma=M_{crc,obs}/M_{crc,cal}$ *moments of crack formation*

Values of crack formation moments are calculated according the methods discussed and compared with test results on beams. Results of comparison are presented in Tables 2 and 3. The average value of ratio at crack formation moments $\gamma_m = M_{crc,obs}/M_{crc,cal}$ characterizes accuracy of method of calculation, while the average square standard deviation of this ratio S_γ and coefficient of variation δ_γ define reliability of the method (see Table 3). It was assessed by verification that distribution of the ratio $\gamma = M_{crc,obs}/M_{crc,cal}$ agrees with the normal law of distribution. Then according to [5] the minimum conventional reliability coefficient k_{min} of a calculation method can be determined:

$$k_{min} = 1/\gamma_m(1-\delta_\gamma \cdot \beta) \qquad (4)$$

where: β is number of standard deviations in accordance with assumed reliability.

The minimum conventional reliability coefficient k_{min} of calculation method makes a part of general safety coefficient. Its values are presented in Table 3.

After comparing results of analysis presented in Table 3 it is easy to discover, that calculation methods 1 and 3 can give quite accurate and sufficiently reliable results of calculation of normal crack formation moments of beams strengthened with external glued reinforcement.

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