Mechanics of Bond Behaviour at the Joint of Normal Strength Concrete Intersecting Beam

Kafeel Ahmed [1], Ahmed El Rajy[2], Riaz Goraya [1] Uzma Kausar [3]

[1] Civil Engineering Department, University of Engineering & Technology, Lahore, Pakistan
[2]Civil Engineering Department, College of Engineering, Qassim University Saudi Arabia
[3] Global Engineering Associates, Pakistan
Kafeel91@gmail.com

Abstract: At the joints of intersecting beams, flexural action of one beam acts as twisting action on the other intersecting beam. This reduces the bond strength of intersecting beams and circumferential tensile bond stress is magnified, reducing the load carrying capacity of the beams. Experimentation was carried out to study the bond behaviour at the joint of normal strength concrete intersecting beams. Nine beams were casted for this purpose. These were divided into three sets. Each set consisted of three beams, two intersecting and one control. All the beams were instrumented with steel and concrete strain gauges and Linear Variable Displacement Transducers. The results of the experimentation showed that at the joint of normal strength concrete intersecting beams, bond strength of primary beam reduced as compared to control beam due to flexural action of secondary beam. This reduction in bond strength of primary beam was 10 to 30 % as compared to control beam. It necessitates the provision of bond improving measures at the joint of high strength concrete intersecting beams. The test results may have an implication of on development length and splice length provisions in the building codes.
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Keywords: Bond splitting stress, Concrete key, Bond stress magnification, Fracture process zone

1. Introduction

The bond behaviour of concrete and embedded reinforcing steel is essential for composite action in reinforced concrete construction [1,5]. The pullout bond tests do not represent the actual stress. This is due to the fact that stress distribution that results in pull out test is different from that present in flexural members. Moreover the transverse confinement provided is also different. This transverse confinement affects the normal pressure on the pull out samples [6,7]. However it guides about the bond behavior to study various parameters, that are a function of bond strength and slip. In reinforced concrete flexural members, the joints are critical as there are more chances of bond failure and subsequent slip of steel relative concrete. Therefore it is necessary to study their bond performance. At this location, column reinforcement is passing thorough the beam reinforcement, leaving little openings for concrete to be placed. Poorly compacted, honey combed and low strength concrete may lead to slippage of steel relative to concrete. Hence reduction in bond stiffness at the joint may result in excessive joint rotation and mid span deflection of the flexural members [10]. Due to critical nature of bond behavior at joints, experimentation involving bond beam tests with models of intersecting beams were planned to study the bond stress and slip relations of steel and normal strength concrete. Bond beam and models of intersecting beams were provided with same development length and were casted from same concrete. Bond beam acted as control beams and beams of intersecting model were named as primary and secondary beams. All these beams and models were tested and data was recoded. This data was processed and relationships were developed. In all the samples, bond strength of primary beam reduced as compared to control beam. Taking into account the mechanics of joint of intersecting beams, the flexural stress of one beam acts in the same direction as the circumferential tensile stress developed around the steel bars of the other beam. This flexural stress magnified the circumferential tensile stress and when it exceeded the tensile strength of the concrete, longitudinal splitting cracks are initiated. Therefore the bond strength of primary beam decreased compared to control beam[10].

2. Bond fracture mechanics

In normal strength concrete, bond strain softening and bond stress redistribution adjoining the reinforcing steel bar take place. The fracture process zone in front of primary and longitudinal splitting bond cracks is large and zone of perfect plasticity is well defined [11, 12,13]. In case of normal strength concrete, the bond fracture energy consists of energy consumed in zone of perfect plasticity and surface energy. The stored strain energy is quite large however, the fracture process zone is big (Figure 1).

This results in gradual crack propagation. The bond stress and slip relationship exhibited by normal strength concrete samples showed a non linear response [8,9,11,12,14]. Cracks in normal strength concrete initiate at lower load level of the ultimate load [15]. Therefore in bond beam tests and model tests, interface de bonding cracks and longitudinal splitting cracks initiate at lower bond stress. Little bond strain energy is accumulated in normal strength concrete keys present between the ribs of the steel bars. Once a crack forms at the interface due to slip between steel and concrete, all the accumulated bond strain energy is poured in to this crack. Since extensive cracking occurs therefore a part of the energy is used in crack propagation and a part is consumed in zone of perfect plasticity. Failure was gradual showing a less brittle response as compared to high strength concrete [10]. This bond fracture behaviour of normal strength concrete can be explained by nonlinear elastic fracture mechanics(NLEFM). During this all the grains present through out the sample yield and gradual longitudinal splitting bond cracks occur at the interface between steel and concrete. Through out the sample concrete shows plastic response. [11,12].

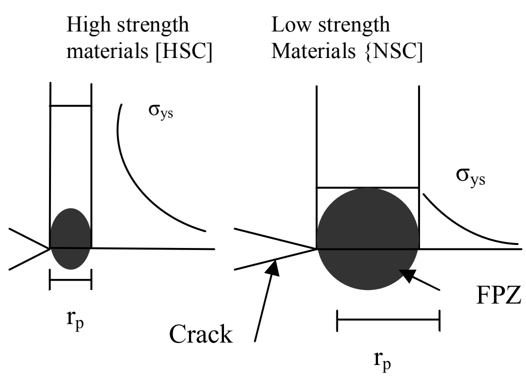

Figure 1. Fracture process zone [11]

3. Materials for experimentation

Cement testing is performed to determine the water demand of the cementitious system. It is required for the effective water/cement ratio of the mix and includes cement, quartz powder and plasticizers. The water demand was determined using different combinations of water alone and water with super plasticizer. Soundness and strength of the cement was ensued by performing relevant tests. Hot rolled deformed steel bar conforming to ASTM C 36 was used. Its geometrical properties are shown in Table 3 and Table 4.

4. Experimentation

Control beams of different concrete strengths were casted from normal strength concrete. In each beam 5.0 d_b embedded length was provided. The objective was to determine the bond strength at the required embedded lengths. PVC pipes were used to break the bond between steel and concrete in the remaining part of the beam (Figure 2). The cross section is rectangular (Figure 3). This was done on the basis of research findings of pull out tests and that of other researchers [8, 9]. Steel strain gauges were used to determine the strain developed during the testing of the specimens. The surface of the steel bar was made smooth and level for the installation of strain gauge. Degreasing, conditioning and neutralization of the steel bar was done as per guidelines provided by the strain gauge manufacturer. Uni-axial strain gauges of 7.0 mm gauge length with pre attached lead wires were fix to the reinforcing steel bars (Figure 4). Moreover concrete stain gauge was used to determine the strain of the concrete (Figure 5). This concrete strain gauge was embedded in polymer concrete to have a perfect bond between polymer concrete and adjoining concrete of the beam. This arrangement ensured the determination of the concrete strain accurately. During pouring, effort was made to avoid any damage to concrete and steel strain gauges and their wires. Immediately after pouring beams were covered with poly ethane sheet to stop the loss of water due to evaporation. Since very little water was used in the concrete therefore its loss may lead to desiccation. The pouring of the beams was done before the initial setting time of concrete (Figure 6). Curing of the beams was started immediately after pouring (Figure 7). Samples for compressive strength of concrete were casted. The compressive strength of the concrete was determined by testing these cylinders in strain controlled universal testing machine (UTM) at 7, 14 and 28 days (Figure 8). The results of compressive strength tests of all the set of beams and models of intersecting beams are given here (Figure 9) and (Table 5).

Demoulding of the beam was carried out 72 hours after pouring. Samples were wrapped with wet jute bags and then poly ethane sheet was wrapped on all sides to stop the loss of water from even jute bags. These were taken out, dried and painted. After that marking was carried out according to the testing scheme of data logger. All channels were reserved for the selected outputs.

Testing was done in strain controlled (UTM) (Figure 10 and Figure 11). Linear variable displacement transducers (LVDTs) were used to determine the slip of steel and concrete. Load cells, attached with the data logger, were used to confirm the load values obtained from the UTM. Similarly strain gauges were also attached with the data acquisition system. Two point load was applied through the load cells. Deflection was measured through the data logger of the universal testing machine…In the first set of the beams, the strength of the concrete used, was 30.0 MPa. The size of the beam was 150.0 x 200.0 x1080.0 mm. First of all steel and concrete acted monolithically and both showed expansion as recorded by strain gauges and LVDTs. However after the failure of adhesion and friction, slip occurred. As the slip increased and steel strain reduced and concrete strain increased. After the failure of mechanical bond, steel bar relaxed and returned back. This was recoded by the strain gauges and LVDTs. Failure started by the formation of flexural cracks present at locations of PVC pipes. As the load was further increased these cracks propagated and multiplied. Then they give way to horizontal bond cracks (Figure 12). Ultimately a v notch bond failure was observed. The concrete strain gauge failed quite earlier. However steel strain gauge recoded the data even when steel bar was compressed.

Similarly 1st model of intersecting beams was casted from 30.0 MPa concrete. Its plan and arrangement were same as that of 1st beam of bond beam test. The arrangement of steel in the form is shown (Figure 13a) and during concreting (Figure 13b). The model of intersecting beams before and after testing is shown (Figure 14). The gird marking and instrumentation was done in the same way as it was that of beams. The load was applied through a special testing assembly. This assembly had same shape as that of X-section to be tested (Figure 15). Two point load could be applied simultaneously on both the beams. Load cell was attached with the data logger. One beam having more effective depth was named as primary beam and other as secondary beam. The whole testing arrangement is shown (Figure 16). In the next 2nd and 3rd of beams and intersecting models the strength of the concrete was increased to 35.0 and 40.0 MPa respectively.

The results of compression test are shown (Figure 9), (Table 5). Testing was done in the same way as that of 1st set. The results were obtained through the data logger, processed and relations were plotted. They are shown (Figure 17 to Figure 22) and all results are compared (Figure 23), (Table.6)

Table 3. Geometrical properties of 13mm diameter reinforcing bar.

Bar Dia	**Rib height**	**Rib Width 'b'**			**c/c Rib spacing 'c'**			**Clear distance between ribs**			**a/c**
	'a'	end	mid	end	end	mid	end	end	mid	end	
mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	
13	**1.2**	2	2	2	7.3	7.6	7	4.9	4.7	5	0.16
		1.5	1.6	1.6	7.7	7.5	7.3	5	4.9	5.4	
		2.2	2.3	1.9	7.4	7.8	7	5	4.7	4.9	
		1.9	1.86	1.76	7.46	7.63	7.1	4.96	4.76	5.1	
		1.905			7.39			4.944			
13	**1.36**	2	2	2.9	7.7	8.8	7.8	4.9	5	4.9	0.17
		1.5	1.54	1.6	7.3	8.7	7.6	5.3	5.2	5	
		2	2.1	2	7.8	8.5	7.6	4.9	5	5	
		1.83	1.83	1.9	7.66	8.6	7.66	5.03	5.07		
		1.86			7.97			5.029			

Table 4. Geometrical properties of 19mm diameter reinforcing bar.

Bar Dia	**Rib height**	**Rib Width 'b'**			**c/c Rib spacing 'c'**			**Clear distance between ribs**			**a/c**
	'a'	end	mid	end	end	mid	end	end	mid	end	
mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	
19	**1.48**	2.1	1.9	2	8	8	8.3	5.2	5.1	5.5	0.18
		1.5	1.4	1.3	7.9	8	8.36	6.2	6.2	6.3	
		2.1	2	2	7.6	7.6	8.2	5.2	5.3	5.3	
		1.86	1.76	1.76	7.8	7.86	8.26	5.5	5.53	5.7	
		1.79			7.97			4.944			
19	**1.51**	2.1	2.3	1.9	8	8	8.9	5.1	5.3	5.2	0.18
		1.7	1.3	1.6	7.4	8	7.9	6.3	6.4	6.2	
		2.1	2	1.9	8	8	8	5.2	5	5.3	
		1.83	1.86	1.8	7.66	8.6	8.26	5.53	5.63	5.56	
		1.83			8.02			5.573			

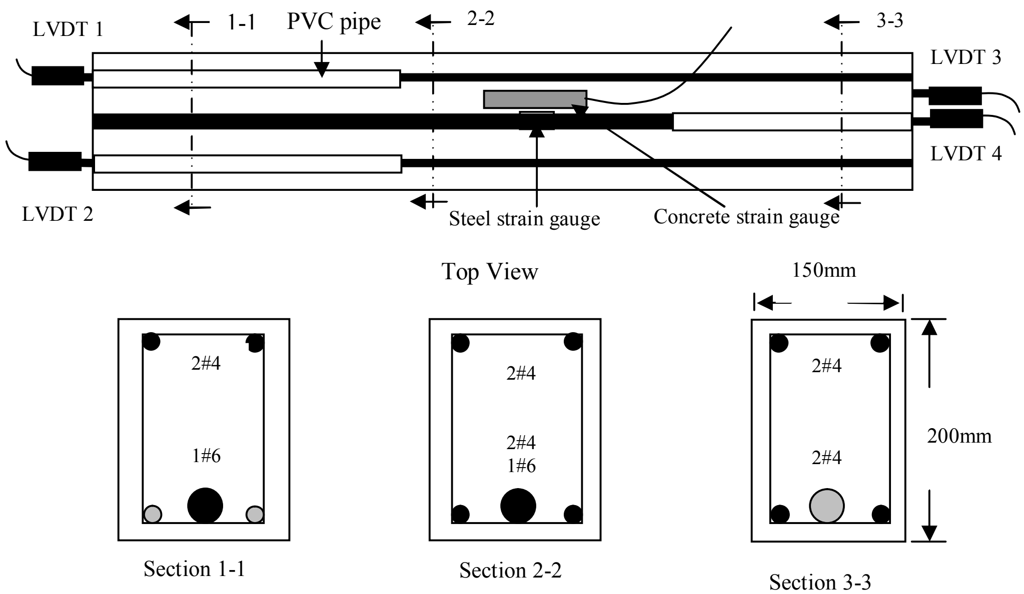

Figure 2. Plan for Beam Test No-1

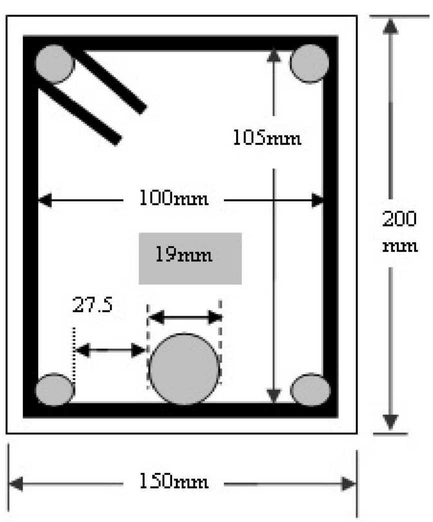

Figure 3. X-secton of the beam

Figure 4. Tied steel with PVC pipe

Figure 5. Tied steel with stain gauges

Figure 6. Process of concreting

Figure 7. Beam immediately after pouring

Figure 8. Compressive strength test in UTM

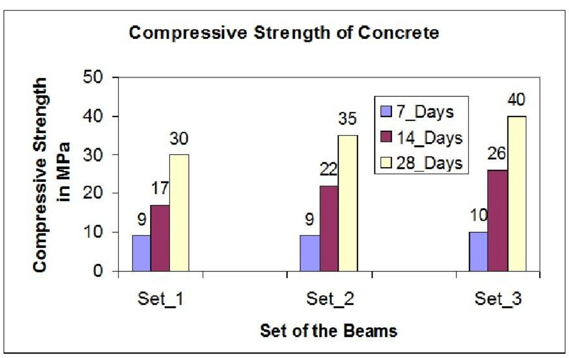

Figure 9. Strength development of concrete

Table 5. Results of compressive strength tests

Age	Sample	Compressive strength		
		Set_1	Set_2	Set_3
Days	Cylinder	MPa	MPa	MPa
7	150.0 mm X 300.0 mm	9.0	9.0	10.0
14	150.0 mm X 300.0 mm	17.0	22.0	26.0
28	150.0 mm X 300.0 mm	30.0	35.0	40.0

Figure 10. Testing of beam in progress

Figure 11. Testing of beam in progress

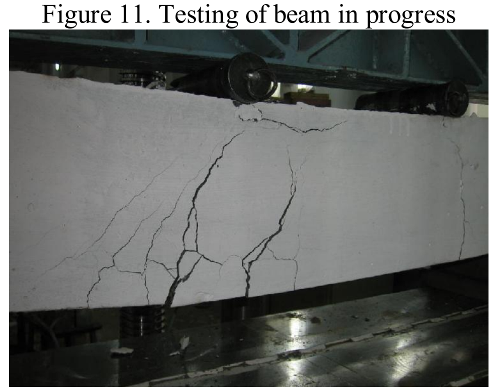

Figure 12(a). Failure in progress

Figure 13(a). Failure in progress


Figure13(b). Concreting in progress


Figure 14. Model before test

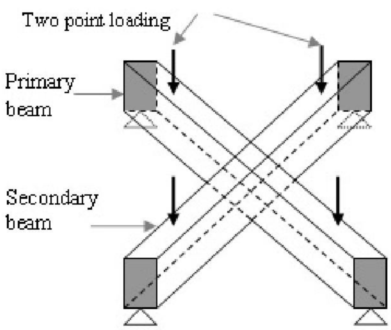

Figure 15. Loading of the model


Figure16. Testing of the model

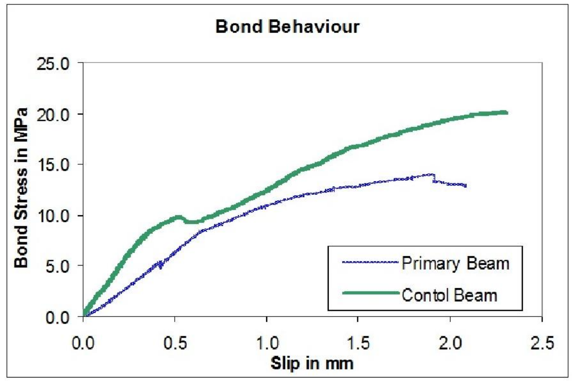

Figure 17. The Bond behaviour of Set_1

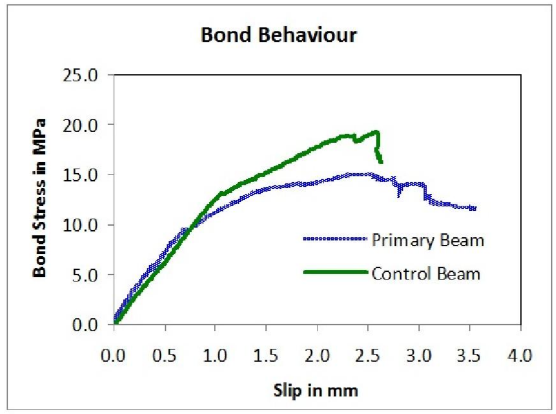

Figure 18. The Bond behaviour of Set_2

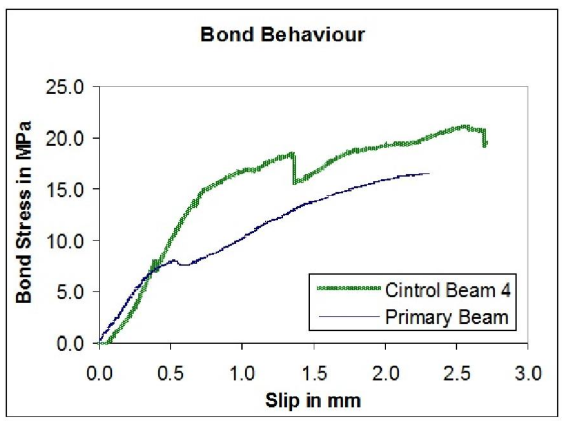

Figure 19. The Bond behaviour of Set_3

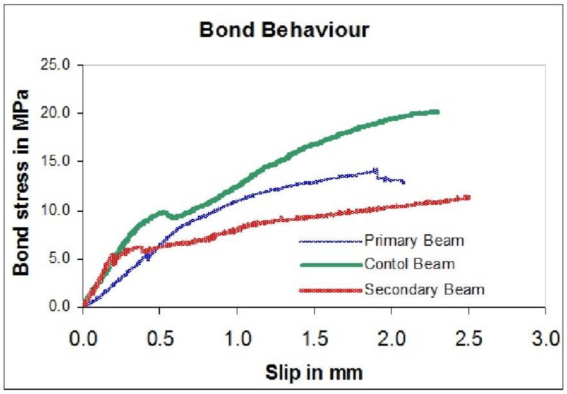

Figure 20. The Bond behaviour of Set_1

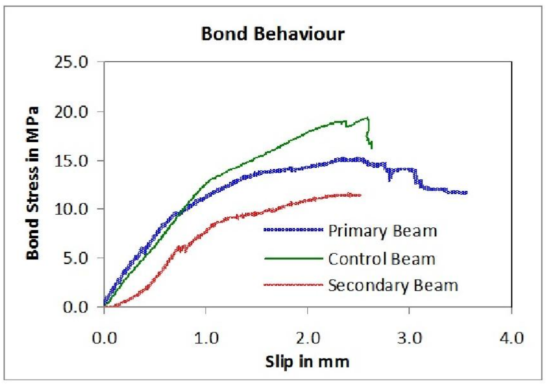

Figure 21. The Bond behaviour of Set_2

Table 6. Comparison of bond strength for all sets of beams

Set No	Bond Strength in MPa		
	Secondary Beam	Primary Beam	Control Beam
Set_1	11.2	14.0	20.0
Set_2	11.5	15.0	19.0
Set_3	12.4	16.0	21.0

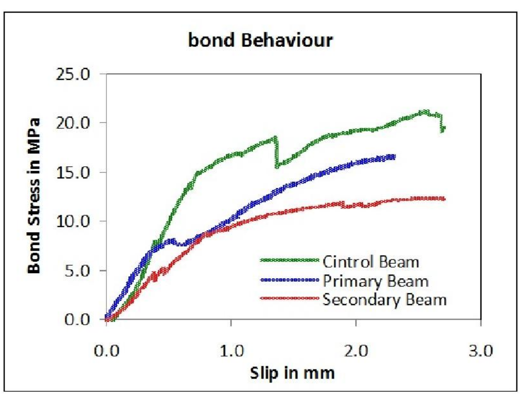

Figure 22. The Bond behaviour of Set_3

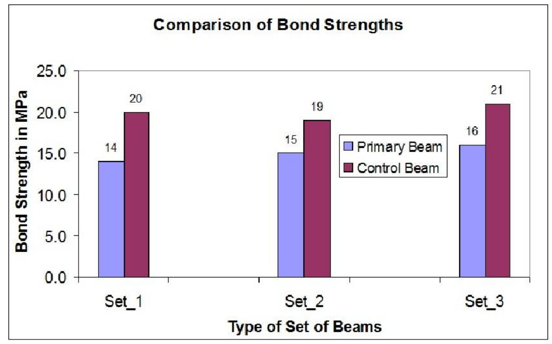

Figure 23. Comparison of bond strength

5. Analysis of the results and discussion

The bond strength was calculated by using the formula as shown below. The strain was measured from the steel strain gauge. Then using the modulus of elasticity of steel, stress present in steel was calculated, from the stress by using the area of steel, force present in steel was calculated. Then this force was divided by the bonded area of the steel bar present over the development length or embedded length.

$$\frac{f_s}{\varepsilon_s} = E_s \qquad (1)$$

$$\frac{A_b f_s}{\pi d_b \, l_d} = U_b \qquad (2)$$

f_s = Steel Stress
A_b = Area of steel bar
ε_s = Steel Strain
d_b = Bar Diameter
E_s= Modulus of elasticity of steel
l_d = Development length

The results of the experimentation show that in 1st set of experimentation the bond strength of primary beam reduced by about 30.0%, in 2nd set by about 21.0% and in 3rd set by about 23.0% as compared to control beam. The comparison of bond behaviour of control beam and primary beam is shown (Figure 23). However, the reduction in bond strength was from 40.0% to 50.0% (Figure 20 to Figure 22). Following equation was developed for the control beam and primary beam of the model of intersecting beam. The co-efficient of correlations of these result varied from 0.98 to 0.99. The value of "α" for control beam ranged from 1.0 to 2.0 and for primary beam 4.0 to 5.0. Similarly the value of "β" for control beam varies from 10 to 12 and for primary beam it varies from 14 to 18.

$$u_c = \alpha s^2 + \beta s \qquad (3)$$

For Control Beam

$$u_p = \alpha s^2 + \beta s \qquad (4)$$

For Primary Beam
u_p = Bond stress of primary beam
u_c = Bond Stress of Control Beam
s = Slip of the steel
α , β = Coefficients

This reduction may be due to the reason that when two intersecting beams are loaded then steel has the tendency to slip relative to the concrete due to difference in stiffness of both the materials. During this conical compression struts are formed around the reinforcing bar ribs. In normal strength concrete, concrete also crushed in front of the ribs. This leads to the slip of concrete key and increase in its diameter. Radial tensile stresses and circumferential tensile stresses generated in the surrounding concrete [10]. The circumferential tensile stress is responsible for the formation of longitudinal splitting cracks around the steel bar (Figure 24). This stress is magnified by the tensile component of the flexural stress of intersecting beam. Hence stress magnification reduces the bond strength of the beam. The mechanics of intersecting model is shown (Figure 25). The mechanism for stress magnification is shown (Figure 26).

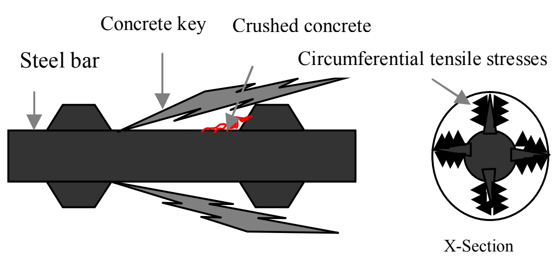

Figure 24. Longitudinal splitting crack formation [8,9,10]

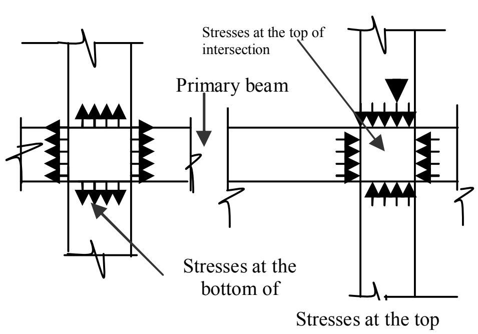

Figure 25. Mechanics of intersection model [15]

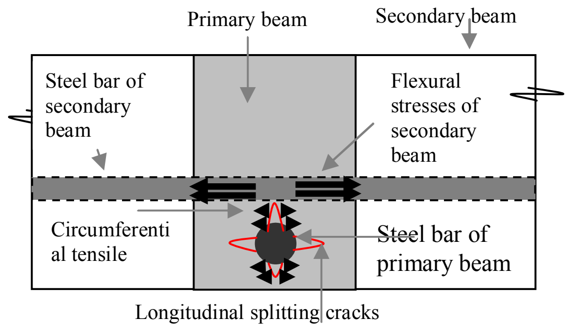

Figure 26. Stress magnification at intersecting beam [10]

6. Comparison with local Bond Constitutive Model

When the bond behavior of the control beam and primary beam of the intersecting model is compared with bond constitutive model given by Eligehausen et al (1983) (ascending part adopted by Comite- International du Beton- Federation International de la Precontrainte Model Code 1990), then it shows that the response of the beam is close to splitting bond failure and not to pull out bond failure. The reason for this behavior is that crushing of concrete in front of the ribs is insignificant and mainly the splitting of the concrete due to circumferential tensile bond stress took place. These circumferential tensile stresses were magnified due to the flexural action of the secondary beam in model of the intersecting beams. This local bond model is shown (Figure 27). This ascending part is mathematically given by Eligehausen et al (1983) and shown below. The descending part could not be determined in this set of experimentation.

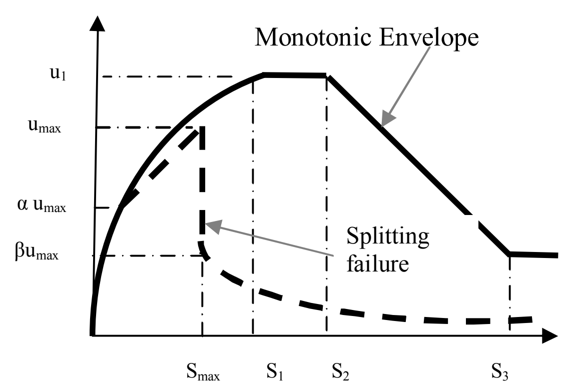

Figure 27. Bond constitutive model given by Eligehausen et al (1983)

$$\frac{u}{u_1} = \left(\frac{s}{s_1}\right)^{v} \qquad (5)$$

For Ascending part [9]

$$\frac{u}{\beta u_{max}} = \left(\frac{s}{s_{max}}\right)^{v} \qquad (6)$$

For descending part [9]

7. Conclusions

When bond behaviour of normal strength concrete primary beam is compared with control beam of the modal of intersecting beams, then it is clear that bond strength of primary beam reduced as compared to control beam. This result is present incase of all the sets of the beams.

The bond strength of primary beam of intersecting model reduced for all strengths of concrete. The magnitude of the reduction varies from 20.0% to 30.0 %.

This may be attributed to the flexural action of secondary beam that magnified the circumferential tensile bond stresses of primary beam, enhanced the longitudinal splitting cracks and reduced the bond strength of primary beam as compared to control beam.

Similarly the bond strength of secondary beam reduced as compared to primary beam. The same circumferential tensile bond stress magnification due to flexural action of secondary beam is responsible for this.

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Corresponding Author
Kafeel Ahmed PhD
Department of Civil Engineering
University of Engineering & Technology, Lahore, Pakistan E-mail: kafeel91@gmail.com

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