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EFFECT OF OPENINGS IN BEAMS – A REVIEW

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***Abstract* — Construction of modern buildings requires many pipes and ducts in order to accommodate essential services such as air conditioning, electricity, telephone, and computer network. Web openings in concrete beams enable the installation of these services. A number of studies have been conducted with regards to reinforced concrete beams which contain web openings. The present paper aims to compile this state of the art work on the type of Reinforced Concrete (RC) beams with transverse web openings. Various design approaches and strengthening techniques are also presented.**

***Keywords*— RC Beams, Deep beams, Web openings, Ultimate Load, Deflection, Strengthening, FRP, Reinforcement.**

I. INTRODUCTION

In general, Beam can be classified into three categories as per its span-to- depth ratio namely Shallow or Normal Beam, Moderate Deep Beam and Deep Beam. In IS- 456 (2000) clause 29, a simply supported beam is classified as deep when the ratio of its effective span L to overall depth D is less than 2. Continuous beam are consider as deep when the ratio L/D is less than 2.5.The effective span is defined as the center to center distance between the supports or 1.15 times the clear span whichever is less. The behavior of deep beams is significantly different from that of beams of more normal proportions, requiring special consideration in analysis, design and detailing of reinforcement. Shallow beams are characterized by linear strain distribution and most of the applied load is transferred through a fairly uniform compression field. It can be analyzed generally by simple bending theory based on assumption that plane sections normal to the axis remain plane after bending. Shallow beams are assumed as one-dimensional linear elements so they resist transverse loading mainly by bending and shear or say mainly by developing flexure and shear stresses. Generally shallow beams predominantly fail under pure flexure failure as it possess very low flexure strength as compared to it shear strength.

Moderate Deep Beams differ from shallow beams considerably. There is a significant effect of normal pressure on stress distribution. The assumption made in simple bending (i.e. plane section remains plane after bending) becomes wrong due to nonlinear strain distribution. In Moderate Deep Beam, the flexure capacity and shear capacity of the beam is nearly same hence the failure of such type of beams is due to both combined effect of flexure and shear. As the beam become deeper the stress distribution becomes non-linear. The stresses at mid span deviate more and more from those predicted by the simple bending theory. Deep beams behave entirely different from normal beams. Normal pressure has greater effect on stress distribution and hence stress distribution no longer remains linear. It has very high flexure strength as compared to its shear strength and hence type of failure is shear predominant failure.

In case of curved beams, along with bending and shear, torsion also comes into picture. This makes the analysis of curved beams more complex.

The inclusion of web openings in reinforced concrete (RC) beams is frequently required to accommodate essential services such as air conditioning conduits, water supply, electricity, and heating ducts. The creation of such openings in existing RC beams produces discontinuity in the normal flow of stresses which would reduce the beam shear capacity and stiffness. Creation of an opening in the web of an existing beam leads to early diagonal cracking and significantly reduces the beam shear capacity and stiffness. The reduction in the shear capacity increases as the opening depth and/or width increases. More significant reduction in the shear capacity was recorded when the opening interrupted the natural load path that is the line connecting the load and support points. This paper provides a review of works performed on the strengthening of beams with openings.

II. LITERATURE SURVEY

A) STRAIGHT SHALLOW BEAMS

Mansur et al. (1983), carried out studies on RC beams with large rectangular openings under pure torsion. It is found that torsional strength and stiffness of a beam decrease with increasing opening length or depth, but appear to be marginally influenced by its eccentricity. The beams fail by the formation of a mechanism with four hinges, one at each corner of the opening.

Naik et al. (1986), conducted studies on optimum hole shapes in beams under pure bending. An effective method of weight reduction for a beam in pure bending is to remove material near the neutral axis, in the form of holes. Minimizing the stress concentration around these holes is an important consideration in engineering design. One of the methods to minimize the stress concentration is to change the hole shape itself until the optimized shape with minimum stress concentration factor is reached within specified geometric constraints and loading condition.

Mansur et al. (1991), carried out an experimental investigation on reinforced-concrete continuous beams with large transverse opening. Variables considered are number of spans, the size of opening, and its location along the span. Failure of the beam occurs by the formation of a mechanism, and the two opening ends represent the most vulnerable locations for the development of plastic hinges. The strength and stiffness of the beam decrease with an increase either in the length or depth of opening.

Thevendran and Shanmugam (1991) investigated the effect of web openings in slender beams. The presence of web openings not only reduces the ultimate strength of beams, but also the lateral buckling capacity. Based on the energy approach, a numerical method was developed to predict the critical lateral-buckling loads of slender, doubly symmetric beams containing unreinforced web openings. The critical loads evaluated numerically are compared with the values obtained experimentally. The study shows good agreement between the numerical and experimental values.

Mansur et al. (2001), examined the strut-and-tie model for the analysis of a reinforced concrete beam that contains geometric discontinuities in the form of a transverse circular opening in the web. A comparison of the theoretical predictions concerning the ultimate strength, mode of failure, and the proportion of the applied shear carried by the chord members above and below the opening shows good agreement with test results. The truss model explains clearly the role of diagonal reinforcement in relieving the concrete distress at the throat section by transferring across the discontinuity a significant amount of applied shear.

Abdalla et al. (2003), carried out studies on reinforced concrete beams with openings un-strengthened and strengthened with FRP sheets. The effect of this strengthening technique on deflection, strain, cracking, and ultimate load was investigated. An experimental investigation on the behaviour and strength of reinforced concrete beams with shear openings was carried out. The presence of an un-strengthened opening in the shear zone of a reinforced concrete beam significantly decreases its ultimate load carrying capacity. An un-strengthened opening with height of 0.6 the beam depth may reduce the beam capacity by 75%. The application of CFRP sheets greatly decreases beam deflection, cracks around opening, and increases the ultimate load carrying capacity of the beam. The use of FRP sheets to strengthen the area around openings may retrieve the full capacity of the beam for relatively small openings.

Maaddawy and Ariss (2012), conducted studies on RC beams with web openings strengthened in shear with externally bonded CFRP composite sheets. The test parameters were the width and depth of the opening and the amount of the CFRP sheets used for shear strengthening. Test results showed that the inclusion of web openings drastically reduced the beam shear capacity and stiffness. External strengthening with CFRP sheets around the opening was found to be very effective in improving the beam shear resistance and stiffness. Increasing the opening width or depth reduced the gain in the shear capacity. Doubling the amount of the vertical CFRP sheets from one to two layers increased the shear capacity but the additional shear capacity gain was not in proportion to the added amount of the CFRP.

Aykac et al. (2013), investigated the influence of multiple web openings along the length of an RC beam on its flexural behavior. Diagonal reinforcement around openings effectively prevented premature failure of some specimens due to Vierendeel action. Longitudinal rebars and full-depth stirrups adjacent to openings and short stirrups in the chords prevented beam-type and frame-type shear failures. The length of the plastic failure mechanism increased in the presence of multiple openings compared to beams with a single opening. The beams were simply-supported at the ends and subjected to six-point bending. The test results were compared to the estimates from available equations.

B) STRAIGHT DEEP BEAMS

Manzur and Alwis (1984) investigated the behavior of reinforced fibre concrete deep beams with rectangular openings in the web. The major parameters of the study were the volume fraction of fibres, opening location, shear span to effective depth ratio and the amount of web reinforcement.

Test results indicate that the amount of web reinforcement, either in the form of discrete fibres or as continuous reinforcement. Available strength equations for non-fibre concrete deep beams are shown to provide a reasonable prediction of the ultimate strength for fibre reinforced concrete.

Haque et al. (1986), investigated the stress distribution in deep beams with and without web openings. The general form of stress diffusion has been established and the critical zones have been identified. The critical tensile and shear stresses have been evaluated and their sensitivity to various span-to-depth ratios and opening positions along the span have been established. Based on stress flow pattern and contour lines of principal tensile stresses, failure mechanisms have been predicted and recommendations have been made for the design of reinforced concrete deep beams.

Yang et al. (2006), conducted study to estimate the influence of web openings in reinforced concrete deep beams. Test variables included are concrete strength, shear span-to-depth ratio, and the width and depth of the opening. Test results indicated that the strengths at diagonal crack and at peak were closely related to the angle of the inclined plane joining the support and the corner of the web opening. Also, the influence of concrete strength on the ultimate shear strength remarkably decreased in deep beams with openings.

Yang et al. (2007) conducted study on reinforced concrete deep beams with openings. The main variables considered were the opening size and amount of inclined reinforcement. An effective inclined reinforcement factor combining the influence of the amount of inclined reinforcement and opening size on the structural behavior of the beams tested is proposed. It was observed that the diagonal crack width and shear strength of beams tested were significantly dependent on the effective inclined reinforcement factor that ranged from 0 to 0.318 for the test specimens. As this factor increased, the diagonal crack width and its development rate decreased, and the shear strength of beams tested improved. Beams having effective inclined reinforcement factors of more than 0.15 had higher shear strengths than that of the corresponding solid beam. Predictions obtained from the proposed formulas have a consistent agreement with test results.

Yang and Ashour (2008), investigated the effect of openings in reinforced concrete continuous deep beams. The main variables investigated were the configuration of web reinforcement around openings, location of openings, and shear span-to-overall depth ratio. Web openings were located in either exterior or interior shear spans and the shear span-to-overall depth ratio was selected to be 0.6 and 1.0. The development of diagonal crack width and load capacity of beams having openings within exterior shear spans were insensitive to the configuration of web reinforcement. For beams having openings within interior shear spans. However, inclined web reinforcement was the most effective type for controlling diagonal crack width and increasing load capacity. It has also been observed that higher load and shear capacities were exhibited by beams with web reinforcement above and below openings than those with web reinforcement only above openings.

Maaddawy and Sherif (2009), examined the potential use of externally bonded carbon fiber reinforced polymer (CFRP) composite sheets as a strengthening solution to upgrade reinforced concrete deep beams with openings. Test parameters included the opening size, location, and the presence of the CFRP sheets. The structural response of RC deep beams with openings was primarily dependent on the degree of the interruption of the natural load path. Externally bonded CFRP shear strengthening around the openings was found very effective in upgrading the shear strength of RC deep beams. The strength gain caused by the CFRP sheets was in the range of 35–73%.

Campione and Minafo (2012), evaluated the influence of circular openings in reinforced concrete deep beams with low shear span-to-depth ratio in flexure under four-point loading. Comparative analysis of the experimental results shows that the effect of the hole depends on its position in the beam; the benefit of the presence of reinforcement depends on its arrangement. An analytical model is proposed to predict the shear strength and corresponding deflection of deep beams with openings and the results are also compared with a non-linear finite element analysis showing good agreement.

Sahoo et al. (2012), conducted study on reinforced concrete (RC) deep beams with large openings. The reinforcement detailing of deep beams based on strut-and-tie models can be complex and, very often, these models may not predict the failure mechanism of deep beams due to localized damages. This study investigates the performance of two RC and two steel fiber-reinforced concrete (SFRC) deep beams with large openings under monotonically increased concentrated loads. The RC specimen with strengthened boundaries exhibited a ductile mode of failure and had significantly higher ultimate strength than predicted by STMs. The SFRC specimens with 1.5% volume fraction of fibers reached much higher strength than the design load and exhibited significant post peak residual strength and a ductile mode of failure.

Alsaeq (2013), investigated the effects of the opening shape and location on the structural behavior of reinforced concrete deep beams, while keeping the opening size unchanged. FEM Analysis was done by ANSYS 12.1. The ultimate strength of reinforced concrete deep beam with opening obtained by ANSYS 12.1 shows fair agreement with the experimental results. The results concludes that the opening location has much effect on the structural strength than the opening shape also placing the openings near the upper corners of the deep beam may double the strength, and the use of a rectangular narrow opening, with the long sides in the horizontal save up to 40% of structural strength of the deep beam.

Mohamed et al. (2014), studied the behavior of reinforced concrete deep beams with and without web openings. Furthermore, the effect of the reinforcement distribution on the beam overall capacity has been studied and compared to the Egyptian code guidelines. The damaged plasticity model has been used for the analysis. Models of simply supported deep beams under 3 and 4-point bending and continuous deep beams with and without web openings have been analyzed. Model verification has shown good agreement to literature experimental work. Results of the parametric analysis have shown that web openings crossing the expected compression struts should be avoided, and the depth of the opening should not exceed 20% of the beam overall depth. The reinforcement distribution should be in the range of 0.1–0.2 beam depth for simply supported deep beams.

C) CURVED BEAMS

Ali et al. (2014), investigated the behavior and performance of reinforced concrete horizontally semi-circular curved beams with and without openings, unstrengthened and strengthened (externally by CFRP laminates or internally by steel reinforcement). The beams were tested under the action of two point loads at top face of mid-spans with three supports at bottom face. The results showed that the presence of opening has a great effect on the behavior and ultimate load capacity of semi-circular curved beams, while the strengthening of these opening by internal steel reinforcement or external CFRP laminates will increase the ultimate load capacity and affect post-cracking behavior and mode of failure of these beams.

Ali and Hemzah (2014), investigated the behavior and performance of reinforced concrete curved ring beams with and without openings, unstrengthened and strengthened (externally by CFRP laminates or internally by steel reinforcement). The beams were tested under the action of four point loading at the top face of mid spans with four supports at the bottom face of the beams. The results showed that the presence of openings has a great effect on the behavior and ultimate load capacity of ring beams, while the strengthening of these opening by internal steel reinforcement or external CFRP laminates will increase the ultimate load capacity.

III. SUMMARY

From this literature survey, following conclusions were made

- *The failure in shallow beams is mainly by flexure.*
- *In case of deep beams, shear failure is observed.*
- *For curved beams, along with bending and shear, torsional failure also takes place.*
- *If the opening size is less than 0.25D, the opening is classified as small.*
- *Strength and stiffness of a beam decrease with increasing opening length or depth.*
- *An un-strengthened opening with height of 0.6 the beam depth may reduce the beam capacity by 75%.*
- *Providing reinforcement around the openings and FRP sheets externally showed increase in the load carrying capacity and crack resistance.*
- *External strengthening with CFRP sheets around the opening was found to be very effective in improving the beam shear resistance and stiffness.*
- *Longitudinal rebars and full-depth stirrups adjacent to openings and short stirrups in the chords prevented beam-type and frame-type shear failures.*
- *The RC specimen with strengthened boundaries exhibited a ductile mode of failure and had significantly higher ultimate strength than predicted by strut and tie method.*

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