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# Behaviour of reinforced concrete deep beams in previous studies

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**Abstract.** This paper is a comprehensive study of the reinforced concrete simple deep beams based on previous experimental and theoretical studies. Furthermore, it is a review of the methods of analysis that recommended by ACI code or suggested by some researchers. The main parameters that were taken into considerations were: shear span to effective depth ratio ( $a/d$ ), amount of flexural reinforcement ( $\rho$ ), web shear reinforcement ( $\rho_h$  and  $\rho_v$ ), steel fiber volumetric ratio ( $V_f$ ), compressive strength of used concrete ( $f_c$ ), existence of openings with different shapes and sizes in addition to strengthening them. Researchers found that increasing  $a/d$  ratio about 50-67% leads to decrease deep beam ultimate capacity by about 17-23%, respectively. Increasing  $\rho$  leads to decrease ductility. Increasing  $\rho_h$  and  $\rho_v$  or both, increases capacity by different ratios. Removing only  $\rho_v$  leads to a decrease in ultimate capacity by about 19%, removing only  $\rho_h$  leads to a decrease in ultimate capacity by about 10%, while removing both, leads to about 31% reduction in ultimate capacity. Using  $V_f = 0.4\%$  causes increasing in cracking and ultimate capacity by about 33% and 11%, respectively, while using  $V_f = 0.8\%$  causes increasing in cracking and ultimate capacity by about 64% and 33%, respectively. Increasing  $f_c$  about 50% leads to increase the ultimate capacity by about 39-52%. It was also found that opening existence decreases the ultimate capacity especially when they lie in the strut paths, more specifically, they decrease ultimate capacity by about 3-69%, while strengthening them by steel plates leads to increase ultimate capacity by about 9-27%.

## 1. Introduction

Reinforced concrete deep beams are structural members having depth much greater than their span, whereas the perpendicular direction thickness is much smaller than either depth or span [1]. These members are used in many structural applications such as diaphragms, water tanks, foundations, bunkers, offshore structures, shear walls, girders used in multistory buildings to provide offsets of columns, and floor slabs subjected to horizontal loads [1, 2].

According to ACI 318-14; [3] "Deep beams are the structural members that are supported on a face and loaded on the opposite face such that compressive struts can develop between the supports and loads. That satisfies (a) or (b): (a) Single forces lie in a distance  $2h$  from support face; and (b) Clear span is not more the four times the depth of the member  $h$ ". From the other side, Eurocode 2 (EC2) [4] describes deep beam as a beam in which the ratio of span to depth is less than three.

### 1.1 Behavior of Deep Beams

Due to their proportions, the strength of deep beams is usually organized by shear rather than flexure. From the other side, its shear strength is meaningfully greater than that predicted using expressions developed for slender beams [5,6,7,8,9]. Thus, special design methods to account for these differences are required. Deep beam stresses, prior to cracking, can be calculated using the well-known two-dimensional elasticity methods. Such studies show that the plane sections before bending do not necessarily remain plane after bending where significant cross sections warping happens due to great shear stresses. As a result, flexural stresses are not distributed linearly even in the elastic range as shown in Figure 1a, which means that the stresses calculating traditional methods cannot be useful [1]. Tests denoted that because of biaxiality of compressive stress in the concrete compression zone, ultimate strain is much larger than usual value,  $\epsilon_{cu} = 0.003$ , may occur [1].

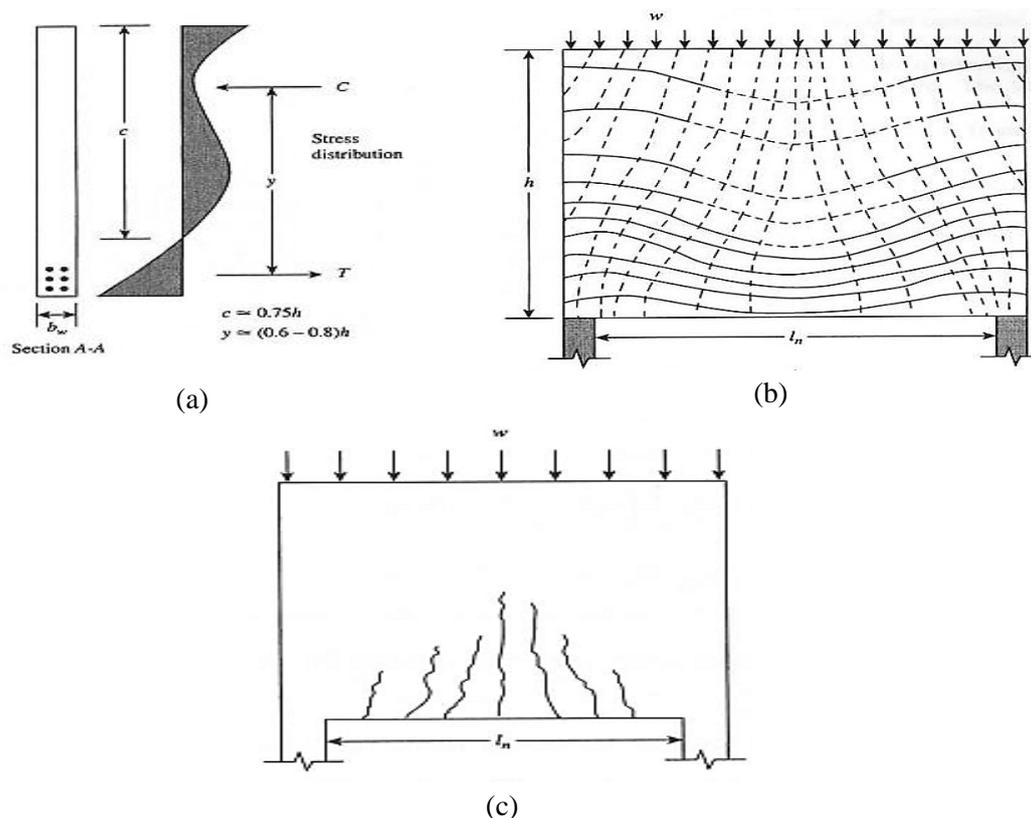


Figure 1a shows the elastic stress distribution at the midspan section of a deep beam, and Figure 1b shows the principal trajectories in top-loaded deep beams. Solid lines indicate tensile stresses, whereas dashed lines indicate compressive stress distribution. Under heavy loads, inclined vertical cracks develop in the concrete in direction perpendicular to the principal tensile stresses and almost parallel to the dashed trajectories as illustrated in Figure 1c. Hence, both vertical and horizontal reinforcement is needed to resist principal stresses. Moreover, tensile flexural reinforcement is needed within about the bottom one-fifth of the beam depth along the tensile stress trajectories as shown in Figure 1b.

Because of the special behavior of deep beams, some codes such as the ACI Code [3] and Canadian Code (CSA) [10] provide guidance for their design, while other codes or standards such as the British standards (BS8110) [11] do not include their design [12,13]. BS8110 obviously states that "for the deep beam design, references must follow professional literature".

Deep beam shear strength is meaningfully more than that predicted using expression developed for shallow beams because the deep beams have a complex behavior and vary in many items, namely: [14]

- 1- After bending, the plane transverse sections do not keep plane.
- 2- As the span to depth ratio decreases, the neutral axis moves away from the loaded face of the member.
- 3- Across the depth of beam, flexural strains and stresses are not distributed linearly [15].
- 4- Shear deformations become significant compared to pure flexure, while in shallow beams, they can be neglected [12].
- 5- Deep beam is under two-dimensional state of stress, whereas shallow beam is under one dimensional state of stress [16].



**Figure 1.** Stress distribution: (a) Elastic stress distribution, (b) Stress trajectories (tension: solid lines, compression: dashed lines), (c) Cracks pattern. [6]

### 1.2 Problem of deep beam

The reinforced concrete beam design and behavior in shear still a concern area for engineers of construction because of the brittle and sudden collapse because of the lack of rational equations of design

in building codes. The modes of shear failure, the mechanism resisting at cracked stages, and the effect of many parameters are currently under investigations by many researchers. [17, 18, 19]

Even if there exist a huge number of researches, there is no agreed rational procedure to predict the deep beam strength. This is mostly due to the highly nonlinear behavior related to the reinforced concrete beam failure. [20]

Regrettably, there is no accurate theory for deep beam ultimate shear strength predicting. The huge number of deep beam strength parameters has directed to a shear failure limited understanding. These parameters include proportion of size effect, arrangement and amount of compressive, tensile, and reinforcement of web, ratio of shear span to depth, steel and concrete properties, loading and support conditions, i.e. support reinforcement anchorage, and size of loading and bearing areas.

## 2. Previous Research Work

Large numbers of research have dealt with the behavior of deep beams and the determination of their capacities. Some of these research works were experimental investigations made by testing some deep beam specimens with a number of affecting parameters. The other researches were theoretical which calculated deep beam ultimate capacity by emerging some theories and suggesting some equations.

### 2.1 Experimental Investigations of Deep Beams without Openings

Mohammadhassani, et al., 2012 [21] discussed the results of eight simply supported high strength self-compacted concrete (HSSCC) specimens having various ratios of tensile reinforcement and web reinforcement with dimensions of 200×500×1500mm. The compressive strength of concrete varied 79-97 MPa as shown in Table 1.

**Table 1.** Specification of tested deep beams. [21]

Beam	f'c (MPa)	$\rho$ (%)	As (mm <sup>2</sup> )
<b>BD1</b>	91.5	0.219	191
<b>BD2</b>	91.5	0.269	236
<b>BD3</b>	91.1	0.410	383
<b>BD4</b>	93.72	0.604	558
<b>BD5</b>	79.1	0.809	760
<b>BD6</b>	87.5	0.938	854
<b>BD7</b>	82.24	1.05	964
<b>BD8</b>	97.2	1.26	1165

The results indicated that beam ductility decreases with increasing the tensile reinforcement ratio. They concluded that shear deformation was so important for deep beams, hence along the midspan section, the distribution of strains was nonlinear. Moreover, the tensile reinforcement strain in the tension zone was more important than the compression zone strain. The authors also concluded that; about 85% of the ultimate load, load-deflection relationships had a linear relationship for high strength over-reinforced web sections.

Choi, et al., 2012 [22] tested four deep beams, two cast with normal concrete (NC) and two with self-compacted concrete (SCC) to study their shear behavior and performance. Both NC and SCC specimens were designed for a high-strength of 50 MPa. The tested beams had 180×360×1700 mm dimensions and  $a/d=1.43$ . Two various reinforcement ratios for web, stirrups spaced at 100 mm and 50 mm, were investigated. The results shown in Table 2 indicated that the SCC deep beams having standard shear reinforcement presented a somewhat higher load carrying capacity than the relating NC deep beams. Whereas the SCC deep beams have jammed shear reinforcement presented a similar load ultimate capacity to the relating NC deep beams. Shear cracks initiated in the range of 33% to 41% of ultimate load at both sides of the parallel layers to the inclined strut and continued instantaneously in the directions of both upward to loading and downward to supporting points. For all beams, at 13% to 17% of the maximum load, the flexural cracks appeared in the middle region and they did not enter into the compression region. Lastly, a sudden shear-compression failure took place in all tested deep beam

specimens. It was found that the initial stiffness was similar for all specimens cast with both NC and SCC.

**Table 2.** Load carrying capacities from the four-point loading tests. [22]

Specimen	Cracking loads (kN)				Ultimate load (KN)	Increase rate%	Failure mode
	Initial flexural	Increase rate%	Diagonal shear	Increase rate%			
NC-100	88	—	225	—	676	—	Shear-comp. failure
SCC-100	108	22	245	9	715	6	Shear-comp. failure
NC-50	128	—	314	—	802	—	Shear-comp. failure
SCC-50	132	4	324	3	796	-1	Shear-comp. failure

Al-Khafaji, et al., 2014 [23] presented results from testing eight simply supported SCC deep beams that had dimensions of 100×330×1050 mm under two-point loading. The ratio of  $a/d$ , compressive strength, steel fiber volumetric ratio and  $\rho_v$  were taken into consideration as parameters of the study. The results indicated that the decrease in the cracking and ultimate loads about 28.6 % and 23.3%, respectively, when  $a/d$  ratio increased from 0.6 to 1. The cracking and ultimate loads increased about 11.7% and 38.8%, respectively, when compressive strength increased from 33 to 65 MPa. Using steel fibers improves cracking and ultimate shear strength by average ratios of 33% and 11%, respectively when 0.4% of steel fibers is used, while they improve these cracking and ultimate shear strength by average ratios of 64% and 23%, respectively when 0.8% of steel fibers is used. When  $\rho_v$  was increased from 0.25% to 0.57%, the ultimate shear strength increased about 10% as shown in Table 3.

**Table 3.** Tests results of SCC deep beams. [23]

Group	Specimen	Conc. type	$a/d$	Steel fibers %	Pu (kN)	Mode of shear failure
A	A1	NSCC	0.6	0	485	Diagonal splitting
	A3	NSCC	0.6	0.4	515	Diagonal splitting
	A4	NSCC	0.6	0.8	560	Diagonal splitting
B	B1	NSCC	1	0	370	Diagonal splitting with crushing of nodal zone
	B3	NSCC	1	0.4	395	Diagonal splitting
	B4	NSCC	1	0.8	465	Diagonal splitting
C	C1	HSCC	0.6	0	695	Diagonal splitting
	C3	HSCC	0.6	0.4	775	Diagonal splitting
	C4	HSCC	0.6	0.8	820	Diagonal splitting
D	D1	HSCC	1	0	520	Diagonal splitting with crushing of nodal zone
	D3	HSCC	1	0.4	630	Diagonal splitting
	D4	HSCC	1	0.8	690	Diagonal splitting

Abdul-Razzaq, 2015 [24] studied the effect of heating on twenty-four small scale simply supported deep beam specimens cast by normal concrete. Specimens were exposed to 300-700° for one hour which caused a reduction in ultimate capacity by about 15-41%. The reason for this capacity loss was attributed to the reduction in concrete compressive strength that took place due to high temperature on one hand and to the variation in thermal expansion coefficient between reinforcing steel and concrete on the other hand.

Abdul-Razzaq and Jalil, 2017 [25] discussed the most variables that investigated in previous research works for continuous deep beams as  $a/d$  ratio, compressive strength of different concrete types, shear web reinforcement in addition to the effect of size, number and location of openings. The results indicated that the shear reinforcement load transfer capacity is more protuberant in continuous deep beams than that in simply supported ones. The crack patterns of continuous deep beams that have web reinforcement are wider developed than those have no web reinforcement. The results also indicated that failure plane formation of the deep beams is difficult to be affected by the type of concrete and maximum size aggregate. The width of the diagonal crack is lesser in normal concrete than in lightweight concrete. The ultimate shear strength increases significantly with increasing the vertical web reinforcement and the compressive strength. Finally, researchers indicated that increasing shear span to overall depth ratio and making web openings decreases the ultimate capacity.

## 2.2 Experimental Investigations of Deep Beams with Web Openings

Hu et al., 2007 [26] tested six simply supported HSRC deep beams with different sizes of openings that have trapezoidal shapes. The studied variable was shear span to height ratios ( $a/h$ ) as shown in Figure 2. The depth of beam specimens was 1000mm, the width was 150mm,  $a/h$  ranged between 0.5 and 1,  $f_c$  ranged from 84 to 103 MPa. All specimens were tested by two-concentrated forces. Test results indicated that the ultimate strength of a deep beam with a web opening is comparable with that of a solid beam, if the web opening does not interpose the strut width between the support and the load point. Otherwise, the ultimate strength will decrease significantly.

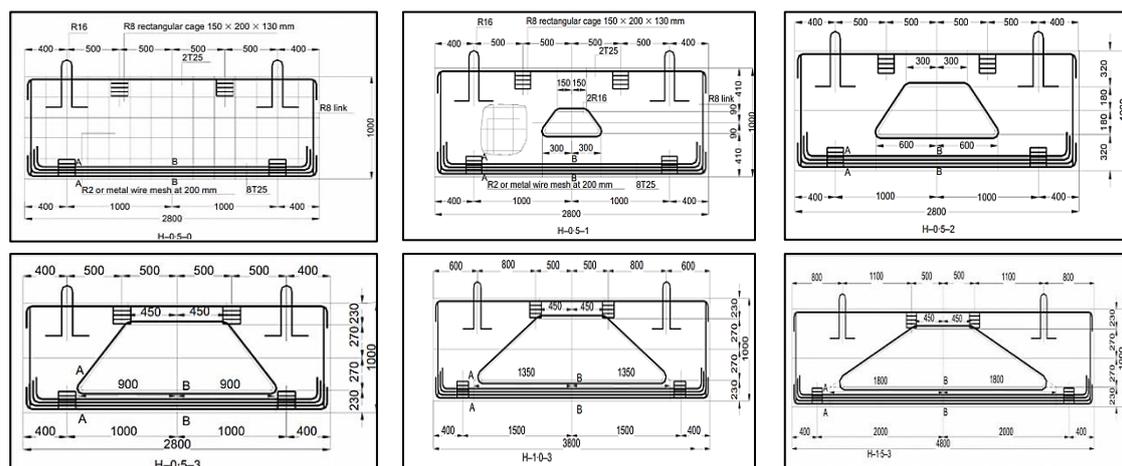


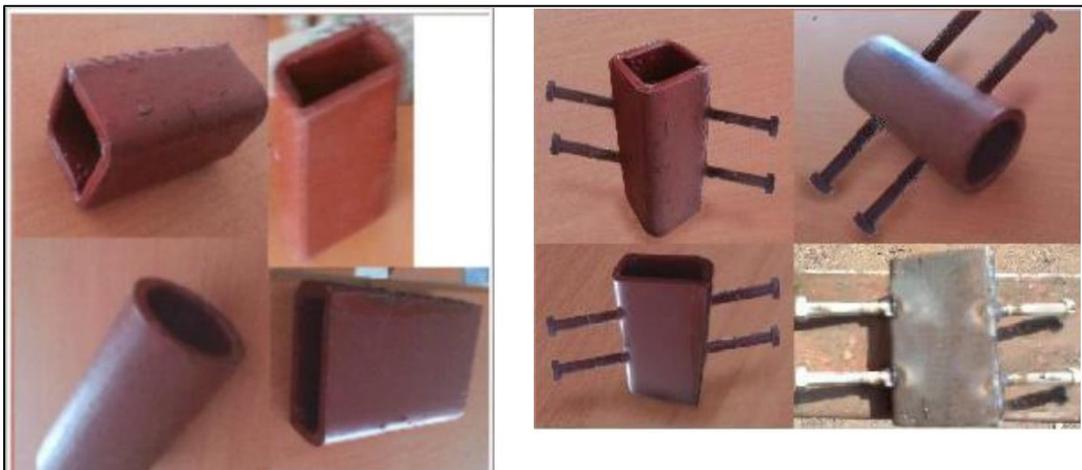
Figure 2. Details of beams in series. [26]

Lee et al., 2008 [27] tested five continuous RC beams to investigate the strength of shear with several positions of circular openings. All specimens were tested by two-concentrated forces. The openings located not in the paths of load. Therefore, the results showed that the beams that had openings lost about 8-13% of the solid beams ultimate capacity. In addition, tests showed that the existence of opening decreased the stiffness obviously.

Nair and Kavitha, 2015 [28] studied strut and tie modelling for deep beams that had openings. Seven 200 x 400 x 800 mm deep beams were tested under a single-concentrated force with different opening locations. Specimens were analyzed in ANSYS 14 software. The results indicated that, the difference between the ultimate loads gotten from ANSYS 14 was about 5% when compared with the experimental tests. The percentage reduction in load carrying capacity was 3% for deep beam with circular or rectangular opening one at center, 19% for deep beam with circular opening one at side, 23% for deep beam with rectangular opening one at side, 38% for deep beam with circular opening at two side and 69% for deep beam with rectangular opening at two side compared with solid deep beam. The rectangular openings caused a more lose in ultimate capacity of RC deep beams than the circular ones. That was clear through the research conducted by Abdul-Razzaq et al., (2016) [29] who also concluded that the ultimate capacity decreased by 17% when  $a/d$  increased from 0.8 to 1.2, and 8% when increasing

size of the openings from 40x40mm to 60x60mm. Also the concluded that the capacity increased by about 52% when increased compressive strength from 25 MPa to 40 MPa. Moreover, the circular shape was better than other shapes of openings such as square or rectangular concerning ultimate capacity saving.

Abdul-Razzaq et al., 2017 [30] investigated the behavior of RC deep beams that had unstrengthened and strengthened web openings. Thirteen specimens were with same dimensions 100 x 400 x 1000 mm. Two openings, in every shear span, one opening was located in the mid of compressive strut. Main parameters were opening shape; square, circular, horizontal and vertical rectangular. The openings were strengthened using steel plates and stud connectors as shown in Figure 3. The results indicated that constructing square, circular, horizontal and vertical rectangular openings led to decrease ultimate capacity by about 21%, 18%, 25 % and 32%, respectively in comparison with the reference solid beam. The strength gained in beams that had strengthened square, circular, horizontal and vertical rectangular openings was about 9%, 13%, 9% & 12%, respectively in comparison with the unstrengthened openings. Furthermore, adding studs to the strengthening plates caused a strengthening gain in square, circular, horizontal and vertical rectangular openings to be about 17%, 18%, 14% & 27%, respectively in comparison with the unstrengthened openings.



**Figure 3.** Steel palates and studs used to strengthen the openings. [30]

### 2.3 Strut and Tie Modeling of RC Deep Beams

A truss of compressive members which represent struts, and tensile members which represent the tensile ties is the assumed stress paths of stresses. These compressive struts and tensile ties are connected together at nodal points. STM represents a simplification of the truss analogy which first showed up in the beginning of 1900's. It developed the foundation of the beam design that depended on the truss model of 45-degrees [31].

#### 2.3.1 Experimental Studies on STM in Modeling RC Deep Beams

Maxwell and Breen, 2000 [32] discussed geometric discontinuities that occur in RC members. Depending on the STM, the design of these unusual members was better understood. Two distinctly different models of strut-and-tie were conducted to design four deep beams with a large opening which caused a geometric discontinuity. The authors defined the performance of four mechanical models that were prepared according to those different designs. The considered simply supported specimens were tested by a point load. Every tested specimen carried an applied load considerably greater than the theoretical factored loads of design. This effective test series exposed the reliability, power, adaptability and predictability of the STM technique.

Brown and Bayrak, 2007 [33] studied the behavior of the deep beams under the influence of various loading types. The specimens were exposed to one, two concentrated forces and uniformly distributed load. Test results displayed the changes in the behavior between specimens that exposed to various load distributions. The differences were clear in the modes of failure, patterns of cracking,

distributions of strain and ultimate capacity. It was clear that the uniformly distributed load had less effect than one or two concentrated loads.

Garay and Lubell, 2008 [34] studied experimental series which were conducted to investigate the behavior of full-scale RC deep beam specimens cast with high strength steel reinforcement. The specimen cross-section width was 300 mm and the height was 607 mm under four-point loading. The authors tested ten deep beams to investigate the  $a/d$  ratio, the longitudinal steel bars ratio  $\rho$  and web reinforcement  $\rho_w$ . The results indicated that the member ultimate capacity decreases as  $a/d$  ratio increases, and as the longitudinal steel bars ratio decreased. The involvement of the web reinforcement meaningfully improved the member ductility and strength. Based on CSA A23.3-04 [35] and ACI 318M-05 [36] requirements, the design of high strength reinforcement deep beams using STM techniques was possible.

Abdul-Razzaq and Jebur, 2017 [37] suggested alternatives for conventional deep beams by reinforcing only struts and ties as compressive and tensile members, respectively, in addition to removing the concrete where these struts and ties do not pass through so as to reduce weight and provide front side area. Three groups of nine simply supported beams were cast. The applied load was the loading type which was one-concentrated load, two-concentrated loads, and uniformly distributed load. The results showed that the suggested frame specimens were worthy substitutes for the original specimens in spite of the ultimate capacity small loss. Nevertheless, these suggested frame specimens already resisted loads more than the STM theoretical factored design loads. Comparing with the references, these suggested frame specimens presented weight reduction about 41-51% in, cost reduction about 4-27% in addition to presenting about 46-55% front side area as shown in Table 4.

**Table 4.** Comparison between all specimens [37]

Group	Specimen	$P_{STM}$ (kN)	$P_u$ (kN)	$P_u/P_{STM}$	% Decrease in						
					Weight			Cost			Front side area
					Conc.	Reinf.	Total Weight	Conc.	Reinf.	Total Cost	
A	DB.2P		562	1.25	-	-	-	-	-	-	-
	STM.2P	447.2	470	1.05	-2.4	38.6	0	-2	-9	-6.17	0
	FR.2P		522	1.16	43.2	17.3	41.5	43.1	-20	4.45	46.4
B	DB.1P		355	1.23	-	-	-	-	-	-	-
	STM.1P	286.5	300	1.04	47.6	48.3	47.6	47	20.8	30.65	51.78
	FR.1P		325	1.13	51	45.7	50.6	49.6	13.5	27	55.35
C	DB.U		547.8	1.25	-	-	-	-	-	-	-
	STM.U	435.7	420.2	0.96	34.3	38.6	34.2	34.4	-8.5	8.3	35.7
	FR.U		505	1.15	43.2	17.3	41.5	43.1	-20	4.45	46.4

### 2.3.2 STM Analytical Studies for RC Deep Beams

Matamoros and Wong, 2003 [38] offered a procedure on STM to predict the reinforcement quantity and the deep beam strength. The authors adjusted the proposed equations of design using experimental test results gotten from 175 simply supported specimens took from previous studies with a maximum  $a/d=3$ . The authors concluded that in the compressive strut, the coefficient of concrete strength reduction decreased with the inclination of strut angle, producing lesser values than those defined in ACI 318M-02, Appendix A.

Brown and Bayrak, 2008 [39] studied data collected from 596 tests of RC beams with  $a/d$  less than 2. The strain energy was studied in different strut and tie models. The favored mechanism was to use single direct strut between one of the reaction points and the load. By checking with the experimental data from literature, results gotten by STM provisions, AASHTO LRFD and ACI 318M-05 Code were verified. The analysis results indicated that the use of both AASHTO LRFD and ACI 318-05 does not present safety levels that meet a 5% exclusion limit.

Abdul-Razzaq and Jebur, 2018 [40] suggested procedures to analyze and design RC deep beams that tested using decentralized loadings depending on STM. The applied three different types of loadings were moved from the supports towards the beam center. Loading types were 2-concentrated forces, 1-

concentrated force and uniformly distributed load as shown in Figure 4. The results indicated that moving load from one of the supports towards the span center leads to increases in the ultimate capacity of beam. That is why, in the case of one-concentrated force, when shear span at left to effective depth ratio became ( $a_{left}/d$ ) reduced from 1.3 to 0.65, the ultimate capacity decreased by 30%. Whereas in the cases of uniformly distributed loading and two-concentrated forces, changing the ration  $a_{left}/d$  from 1.02 to 0.37 led to 30.5% decrease in ultimate capacity.

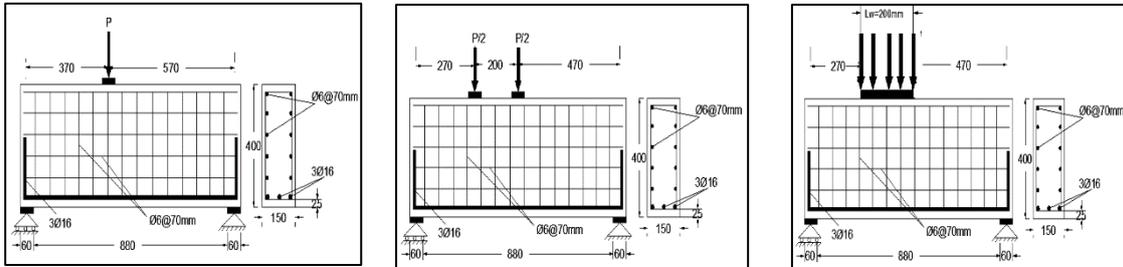


Figure 4. Different types of loadings [40]

### 3. Concluding Remarks

From the previous mentioned studies, the following remarks are drawn:

- 1- The tensile reinforcement strain in the tension zone was more important than the compression zone strain.
- 2- The ductility for deep beam decreases with increasing the ratio of tensile reinforcement.
- 3- The shear deformation was so important for deep beams, hence along the midspan section length, the distribution of strain was nonlinear.
- 4- The SCC deep beams having standard shear reinforcement presented a somewhat more ultimate capacity than the related NC deep beams.
- 5- The cracking and ultimate loads increase, with increasing compressive strength and longitudinal steel bars ratio and decrease with increasing shear span to effective depth ratio.
- 6- The involvement of the web reinforcement meaningfully increases the ductility and strength of member.
- 7- The ultimate capacity of a deep beam that has a web trapezoidal opening is comparable with a solid beam, if the opening of web does not interpose the force path that is, it does not reduce the strut width between the load point and the support.
- 8- Exposing Deep beam to 300-700° temperature for one hour leads to a reduction in ultimate capacity by about 15-41%.
- 9- The shear reinforcement load transfer capacity is more protuberant in continuous deep beams than in simply deep beam.
- 10- Failure plane formation in deep beams is difficult to be affected by the type of concrete and maximum size aggregate; in addition, the width of this diagonal crack is lesser in normal concrete than in lightweight concrete.
- 11- The shear capacity and stiffness of a solid deep beam is higher than that contains openings.
- 12- The ultimate capacity of the deep beam that has a circular shape was higher than deep beam that contains other shapes of openings such as square or rectangular.
- 13- Adding stiffening studs perpendicular to strut increases the ultimate capacity of the deep beam.
- 14- Applying different types of loadings leads to different modes of failure, patterns of cracks, distribution of strain and ultimate capacities.
- 15- The uniformly distributed load was a much less severe loading type than one or two concentrated loads.
- 16- The coefficient of strength reduction for concrete in the main strut decreases with decreasing the inclination angle of the strut.
- 17- The ultimate capacity of the simply deep beam decreases when moving load from one of the supports towards the span center.

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