Continuous Deep Beams Behavior Under Static Loads: A Review Study

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Abstract. Few studies discussed the continuous deep beams CDB behaviour in spite of its great importance in building constructions due to the usual use in bridges and tall buildings as a load distributor. The behaviour of CDB shows a different behaviour when comparing with the simply supported one, so the expected behaviour of SDB does not match with the CDB. So, this paper deals with reviewing the behaviour of CDB in the past researches. It has been concluded that, the CDB resist the applied loads by flexural and shear together, the flexural behaviour appears at the first loading stage then the beam start to resist by shear capacity. The amount of resistance of beam by flexural depends on a/h ratio, main and web steel reinforcement and concrete compressive strength. Flexural behaviour may not appear for very small a/h ratio or over main reinforcement. Also, main steel reinforcement at both top and bottom of beam does not reach to yielding point expected one case, which is, the main steel ratio is less than 0.6% .thereby, tie failure will governs.

1. Introduction
Concrete deep beams in accordance to ACI 318 -19 code may defined as a structural member in which loads subjected on one face and supported on the other opposite face in a manner allows a compression struts to form between the loading and the supporting points and a tie between supports [1]. It is used in constructions as a load distributer element (due to its high resistance capacity) just like girders, tanks, high rise buildings, pile caps, offshore structures and foundation walls (see Figure 1& Figure 2) [2–6]. Deep beams at tall buildings (which behaves as a transferring member for the heavy loads and directly bears the force from the upper shear columns or walls), the span-depth ratio has not to be greater than 8 and favourite to range between (3–6) [7]. There are many differences between shallow and deep beams due to the high shear deformation of deep beams and their nonlinearity of straining. So the conventional elastic beam theory (Bernoulli beam theory) cannot be applicable and have to be replace by Timoshenko beam theory [5]. The simply supported deep beams may satisfy one of the following conditions so as to behave as a deep beam which are: clear span to total depth less than or equal to four for distributed load (less than or equal to two for point load), and the concentrating load applies at (a) distance within 2h form the support face [1]. The critical section of shear is of (a/h ≤2) where a is the distance from concentrated load to middle line of supporting and d is the total beam depth without cover size [1]. For continuous deep beams a/h ratio has not to be greater than 2.5.

Very little researches deals with continuous span beams [2, 10]. There are many behaviourally difference between SDB and CDB [11,12] such as; (1) the shear failure pattern generates below the loading section at SDB but at both CDB sides, (2) large shear and negative moment occurred at middle interior support of CDB while for SDB the maximum shear magnitude occurred at the lower bending moment point (3) the CDB in contrast to CDB does not exposed to supporting settlement [8] and (4) the CDB strut has a great degree of deterioration than SDB at the same parameters and specimen details [13]. The diagonal
cracks in CDB occurred in higher degree of deterioration and lower effected by compressive strength of concrete comparing with SDB of the same parameters [13]. The strut tie method provides by ACI 318-19 code showed less safety for CDB than SDB [13]. CDB failure amount and type is not warranted due to two reasons: the first one is the capability of differential settlement accrual and the second, the inflecting point formed nearby the critical shear failure zone of strut, so that the empirical equations of the ACI 318-19 code may be more accurate for SDB [10]. The most effective factors on CDB shear ultimate capacity are the shear span to depth ratio and the compressive strength of strut [14].

![Figure 1. CDB as a load distributor](image1)

![Figure 2. CDB at buildings](image2)

The moment at the central support has been found equals 1.17 times the moment under the loaded point [15]. This paper involves understanding the behaviour of CDB by reviewing the few and limited past researches in the following sections.

2. Web Reinforcement effect
Shear reinforcement in deep beams represented by longitudinal and horizontal web reinforcement (logically, in addition to concrete contribution). The improvement in beams shear capacity due to such reinforcement depends on bars area and the spacing between the stirrups. It has been found that, for continuous deep beams, adding both types of web reinforcement enhanced shear capacity of beams in a magnitude depends on the steel amount. But, the vertical web reinforcement provides more significant strength than the horizontal one (because of the contribution of this reinforcement with concrete to resist the shear stresses) and allows the beam to show more deflection. In contrast with the horizontal reinforcement which reduce the beam displacement (due to confinement effect) [6,16]. Reducing beam deflection pushes the beam to fail by diagonal shear faster. Noting that, the effect of increasing horizontal shear reinforcement has no significant effect on beam strength when a/h ratio is more than 1, while for a/h less than 0.6, beam shear capacity increases with horizontal shear reinforcement increment [17].

In simply supported deep beams, the horizontal web reinforcement has the significant effect on beam strength. Casting continuous deep beams without vertical web reinforcement makes the beam collapse as a brittle and in every increment in vertical web reinforcement the beam became more and more ductile [16,18].

3. Shear span to depth ratio
CDB behaviour approaches to be flexural with the smaller a/h ratio, and its shear strength capacity increased linearly with a/h reduction [11]. The smaller a/h ratio shows less deformation capacity of CDB also ductility and beam load capacity [18]. Beams tested with the same a/h but with different (a) and (d) values and increasing amounts of main steel reinforcement has no impact effect on beam stiffness [19]. The crack pattern effected at the first degree by a/h ratio, for the same steel ratio amounts,. The larger a/h the earlier flexural cracks formatting and less visible diagonal shear cracks [18]. Both compression and shear stress at the strut increases when decreasing the beam depth [20].
4. Main reinforcement impact

The percentage of main reinforcement effects on CDB behaviour. Rodriguez et al.[21] introduced a load capacity versus main reinforcement percentage (Figure 3) for different diameters of steel stirrups to study beam behaviour affected. It can be noting that, increasing the amount of main-reinforcement greater than 1% leads to steady the failure load, curves tend to be asymptotic, in another word, for high amounts of steel main reinforcement, the failure is limited by strut strength capacity[17,21]. It has been also noting that, for main reinforcement amounts less than 0.6%, the structural failure is conditioned by the tie. Also it can be noting that, the load capacity increase when increasing stirrups diameter.

![Figure 3](image)

**Figure 3.** Effect of main steel reinforcement ratio on loading capacity of CDB [21]

5. Cracking patrons

At the final stages of loading, the crack patrons at both sides going to be symmetric at final failure load [23] as shown in Figure 4, but unsymmetrical for beams without shear reinforcement [19]. The number and width of cracks minimized when increasing beam depth (h) due to the increment of energy releasing rate and expansion of crack width which will cause a brittle failure. The shear failure dominates the collapse types in deep beams [19,24]. The shear failure is brittle which will decrease the beam ductility and decrease the structural member strength [24]. The diagonal shear exterior span cracks forming suddenly just when approaching to the final failure load [18,19]. After the first diagonal crack, at the middle support, the amount of load transfers to the external support becomes higher [19]. If the a/h ratio is very small, no flexural cracks appeared till failure load neither in sagging nor hogging regions [25].

![Figure 4](image)

**Figure 4.** Typical shear cracks of CDB [23]

Since the CDB failure dominates by shear, then the flexural positive cracks has little effect on beam stiffness while the diagonal ones have the most effective impact[23].

Table 1 shows the amount of loading at first visible cracks for the pervious researches it can be concluded that, shear cracks may appears at (33-40)% of the failure load for beams without any shear reinforcement and this variation depends on a/h ratio and main steel reinforcement amount. For beams with a/h ratio=1, first diagonal crack occurs at about (23-49%) of the overall beam capacity relenting on main and shear steel reinforcement amounts and concrete compressive strength.
**Table 1.** loading stages of appearance shear and flexural cracks for CDB

| Ref. | a/d  | $\rho$ (%) | $\rho_v$ | $\rho_h$ | $f'c$ | *1st +ve crack | **1st –ve cracks | *** 1st shear crack |
|------|------|------------|---------|---------|-------|----------------|-----------------|-------------------|
| [6]  | 1    | 2.13       | 0.25    | 0.34    | 36    | 20-23          | 80              | Larger than 23    |
| [24] | 1.4  | 1.29       | 25      | 22      | 33    | 26             |                 |                   |
| [18] | 1    | 4.2        | 0.33    | 0.33    | 25    | 25             | 80              | 30                |
| [19] | 0.5  | 0.1        | 0       | 0       | 0.34  | 32.4           | 80              | 40                |
|      | 1    | 1          | 1.8     | 0.56    | 0.56  | 35             | 0               | 32                |
|      |      | 0.5        | 1.3     | 0.56    | 0.56  | 40             | 0               | 46                |
|      |      | 0.33       | 0.9     | 0.56    | 0.56  | 38             | 0               | 43                |
| [27] | 1    | 0.89       | 0.22    | 0.22    | 0.22  | 30             | ---             | ---               |
| [28] | 1.67 | 1.53       | 0       | 0       | 0.38  | 13             | 13              | 33                |
|      | 1.33 | 1.53       | 0       | 0       | 0.38  | 14             | 14              | 34                |

*Load percentage at first positive flexural visible crack (%)*

**Load percentage at first negative flexural visible crack (%)**

***Load percentage at first shear visible crack (%)***

6. **Concrete straining**

It is worth to mention that, the surface strain at first loading stages and before cracking, shows a linear relation, but after cracking the behaviour transfers to the nonlinearity with a significant large and rapid amounts of straining [6]. The straining rate increases when the beam is a horizontal web reinforced [6]. The maximum compression straining at diagonal strut was about 0.002 at reference [24].

Before first cracking, both top and bottom steel reinforcement showed a compressive straining, which soon convert into a tensile one after the appearance of the first diagonal crack due to tie arch action [19].

7. **Reinforcement bond**

CDB easily to loss the bonding of longitudinal reinforcement and concrete when exposed to the same rotational bending moment at the two sequenced spans [20].

8. **Steel straining**

Both top and bottom steel reinforcement does not reach to yield under loading conditions [18,19]. The failure in CDB is governed by shear. The tensile bottom strain reinforcement higher than the top one due to the stress redistribution [18]. The top longitudinal steel bars at initially loading (before appearance of the first cracks) stages showed a compressive strain, then, at the moment of appearing the first diagonal crack, the strain at top reinforcement bars convert into tensile strain. That while lead to concluded that, the incrementing rate of strain due to tie action versus applied load has nearly independent on concrete type [25]. The highest tensile straining occurs at the region of cross sectional member cracks but without yielding [19]. The smaller maximum aggregate sizes in SDB leads to lower tensile strain in the top steel bars, which mean that, the increase of load capacity of beams due to the enhanced aggregate interlock may produces a higher load transfer by tie action [25].

9. **Differential settlement**

Structural members usually exposed to differential support settlement when the foundation is unevenly settles, soil expand and when contracts [29]. It may cause a localized extra cracks. As an example, the CDB designed to transfer heavy loads from construction to at least three supports, when the middle support settles in a high rate in accordance to the two externals, a hogging moment develops over the mid span beam [29,30]. Differential settlement occurs due to the longitudinal strains varying nonlinearly along the beam depth [15]. Building may still behave elastically after 25 mm of differential settlement, beyond, the inelastic behavior generated in the lower floor [31]. Supporting differential settlement
effected by many parameters, like: spacing and ratio of the steel longitudinal bars, compression and tension stresses of reinforced concrete, and the stiffness and location of the supports [32]. The effect of increasing support stiffness has been studied by Naser et al. [33], the middle support stiffness multiplied by 0.5, 2 and 5 times the original one. The load displacement curve for the specimen has been listed in Figure. It has been concluded that, the effect of spring stiffness is not linear as expected. Minimizing support stiffness to the half reduces the beam capacity by 17% [33]. It can be noted that, the significant increment in the middle support stiffness leads to major transfer the forces to the stiffer region of beam [33].

![Figure 5. Load versus deflection curves effected by support differential settelement [33]](image)

10. **Concrete properties influence**

Incrementing concrete compressive strength offered more brittle behaviour and showed larger load carrying capacity so as stiffness, also rises the ultimate load of the CDB due to strut compressing [17,26]. Doubling concrete compressive strength increases CDB capacity in a range 6-21% [23].

The aggregate interlock across shear cracks shows an impact effect on CDB and SDB mechanisms, because the shear stress transferred by frictional effect and aggregate interlocking [34]. 50% of the transferring shear stress is carried by aggregate interlock at slender beams [35] but the contribution of aggregate interlocking in transferring shear stresses increases as the a/h ratio decreases as a result of the steeper angle of diagonal cracks [36]. The contribution certainly depends on aggregate specifications like: size, shape, aggregate strength and concrete compressive strength [37]. The aggregate size incrementally proportional with the ultimate shear capacity of shallow beams[38]. While inversely proportion has been found between the smoother aggregates and the beam capacity [39]. Increasing beam size without increasing aggregate size causes to minimize the aggregate interlock and thereby the overall shear strength of beams [40]. Beam deflection of SDB decreases while the incrementing of maximum aggregate size [25].

Some few researches studying the impact of adding scraped cramped rubber into concrete mixes of CDB for dynamic absorption purposes [41-43]. It has been found that, adding rubber as a gravel replacement leads to dropping the compressive strength as well as the overall ultimate load of continuous deep beams [41,42] (replacing 10 and 15% of sand by rubber decreases the ultimate load failure by 33 and 45% respectively, so it’s not recommended to replace by more than 10% [42]).

11. **Shear failure carrying capacity**

The most effective factors effects on the shear capacity of section are: ratio of flange width to gross width, span/depth ratio and the compressive strength of the concrete [44].

Experimental work tests showed that, the design equation provides by ACI -318 code (so as EC2-2004 [45]) are a lower bound theory. i.e. the failure load showed in experimental tests more than the theoretically calculated using the equations [13,18,24,30,43]. Verification factor has been calculated to discuss the difference between experimental tests and empirical design equations (of ACI 318-19 and EC2-2004) and found to be 1.004 and 1.158 % respectively [43]. EC2 is more conservative for CDB
The underestimation occurred because the fact that the CDB equations derived from SDB tests [18].

12. Continuous deep beams strengthening
Many researches at literature involves the strengthening of CBD using different methods like: carbon fiber near surface mounted[46,47] and fiber reinforced polymer[48–53]. Bdari et al [47] concluded that, the orientation of strengthening bars had a big significant effect on the ultimate load strength of CDB. Horizontal CFRP bars increases the overall ultimate strength by about 25% and the vertical by about just 6 or 12%. This behaviour occurred due to the effect of transferring stress from strut zone to the overall horizontal length of CFRP which prevent the stress to connect at small areas. But, generally, these values cannot be generalized because it is depends also on another factors as: fibers type, thickness, long and gluing. Using NSM instead of CFRP provides more ultimate strength [47]. Increasing concrete compressive strength from 40 MPa to 60 and 90 MPa leads to decreasing the CDB deflection by 17.8% and 38%, respectively [33].

13. Influence of beam web opening
Sometimes, the existence of opens in CDB is necessary for facilitate essential services and utilities. For multi-story buildings in particular, the savings in story height that achieved at each level gives a substantial savings in the surface area of partition walls, length of riser ducts, and overall loads on foundation. The losing in ultimate load depends on the size and number of opens[21]. The most favourite position for the open is at point C (see Figure 6), where this position has the less or not effected by the stress waves which transfer as strut and tie. The interior region of beam (i.e. points D, E, J and K) caused usually deceasing in beam capacity by (30 to 40%) because it is a critical area due to the high amounts of stresses which it is exposed to. Opens at F point, a load capacity that is far beyond the rest of the positions analysed in the inside area, so it is the most favourite point for CDB. Opens at point like B minimizing the beam capacity by less than 5%. Figure 6 shows details for open position and the beam capacity decreasing.

Figure 6. Effect of opens location from the struts and ties on the loading beam capacity[21]

Opens of (150×150 mm) size and numbers of (1&2) in each span leads to reducing beam capacity by (46% and 49%) respectively. The reduction in strength can be recovered by many ways of strengthening.
like CFRP. Since the loads subjected on CDB transfer as struts and ties, then there are a regions in CDB may opened due to its low participating in strength.

14. Continuous deep beams capacity calculation

Elastic analysis for SDB or even for CDB provides us by an elastic ultimate load in an acceptable degree of accuracy but it is not suitable for nonlinear analysing due to the deep beam nonlinearity and the contra-flexure point of the CDB. For analysing the CDB many methods may be used like: finite element analysis, ACI-318 code equations(STM), Kong Robins and sharp and truss model [10]. The artificial neural network (ANN) and multi linear regression also used for estimating the ultimate load and deflection of concrete CDB. When calculating the capacity of 75 CDB tested experimentally with the ANN method, getting a 99.13% degree of correlation and a 81.16% for the multi linear regression [54]. STM depends is a lower bound theory based on material ultimate strength and forces equilibrium conditions [19]. For low and medium concrete compressive strength, the strut and tie method introduced a good agreement with a different design codes procedures [55]. There are more than one mode of strut ant tie shape per one loading case for CDB in contract to SDB (see Figure ). Mode estimation governs a significant effect on the failure load calculation, and that one of the reasons which made a difference between experimental results of beam and the theoretical calculations. Usually, that model is the best in which the loads follow the path with the least force and the least deformation [12].

![Figure 7. CDB Strut and tie models [11]](image)

Estimating CDB capacity may determine using strut and tie method STM, in which it depends on the plastic theory, balance theory and yielding state theory [12]. The discontinuous regions considers as a truss where tension and compression forces transfer to support by struts and ties as shown in Figure . The nodes collect struts and ties. The CDB shear capacity represented by both internal and external reactions ($V_E \& V_I$) and it can be determined as the following:

$$F_E = v f' c b W_{ES}$$  \hspace{1cm} (1)

$$V_E = F_E \sin \theta$$  \hspace{1cm} (2)
\( F_1 = v^f c b W_{1S} \)  
\( V_1 = F_1 \sin \theta \)  
\( \theta = \tan^{-1}\left(\frac{h - c - c'}{a}\right) \)

As ACI-318 recommendations, the angle \( \theta \) must not to be more than 25°. The failure load of beam can be determined by evaluating the average of lower and upper strut width:

\( W_{ES} = \frac{W_{ESL} + W_{ESB}}{2} \)

\( W_{1S} = \frac{W_{1SL} + W_{1SB}}{2} \)

The effective width of the strut can be estimated from the following equations. It's clear to noting that it depended on bearing plate's width, depth of ties, and angle degree.

\( W_{ESL} = 0.5 LLP \sin \theta + Wt \cos \theta \)

\( W_{ESB} = LEP \sin \theta + Wbn \cos \theta \)

\( W_{1SL} = 0.5 LLP \sin \theta + Wt \cos \theta \)

\( W_{1SB} = 0.5 LIP \sin \theta + Wbn \cos \theta \)

\( P_t = 2(V_1 + V_E) \)

**Figure 8.** STM of CDB, a-Truss model, b-loading joints, c-intermediate supporting joint[43]

**15. Conclusions**

1. The horizontal shear reinforcement has no effect on the overall shear capacity if the CDB behaves as shear member. Likewise, the CDB which under a flexural behavior, its failure capacity does not effected by the increment in increasing steel stirrups.

2. Failure mode or even first crack appearance, not necessarily dependent only on a/h ratio. If the beam was of a/h equals 2.5 and it was over reinforced, the flexural behavior may appears even the a/h ratio approaches to the flexural. So as for the over shear reinforcement.
3. Horizontal web reinforcement improves shear strength of CDB but in a percentages lesser than the vertical ones.
4. CDB designed to resist the applied loads by flexural and shear together, but increasing horizontal web reinforcement enhances beam flexural capacity and minimizing its deformability, that will push the stress to the weaker paths which are the strut, thereby the beam behavior may convert to shear only for over main or horizontal beam reinforcement.
5. Smaller a/h ratio, the greater shear resistance and the lesser deformability of CDB.
6. a/h ratio larger than 1, does not effected by horizontal web reinforcement, while a/h less than 0.6, enhanced beam to shear capacity.
7. Neither top nor bottom main steel reinforcement reaches to yield during loading in many researches, just in one case, which is when the main steel reinforcement is less than 0.6%, then the beam may failed by tie failure.
8. Crack patterns are going to be symmetric just at the final load steps of loading, and it type (flexural or shear cracks) depend on some factors like: a/h, steel reinforcement and concrete compressive strength.
9. Flexural cracks has little effect on beam stiffness in contract to the shear cracks.
10. The failure in CDB is always shear, so there is no yielding strain neither in top one bottom steel reinforcement. The bottom steel reinforcement shows more straining than the top. The latter shows a compression strain till the appearance of the first crack, then it converts into tensile due to tie behavior.
11. CDB exposed to differential settlement due to many factors, the allowable differential settlement has not to be more than 25 mm.
12. Contribution of aggregate interlocking in transferring shear stresses increases as the a/h ratio decreases as a result of the steeper angle of diagonal cracks.
13. In case of the necessity of an open required, the least harmful position is that between the two struts.

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**Nomenclature**

| Symbol | Definition |
|--------|------------|
| a      | Beam shear span |
| b      | Beam width |
| c`     | Upper concrete cover |
| c      | Lower concrete cover |
| F₁     | Interior struts loading capacities |
| Fₑ     | Exterior struts loading capacities |
| h      | Total beam depth |
| P𝑡     | Total calculated load |
| v      | Concrete effectiveness factor |
| W₁ˢ    | Interior width of strut |
| Wₑˢ    | Widths of exterior concrete compressive struts |
| Wₑˢₜ   | The upper exterior strut widths |
| Wₑˢᵇ   | Lower exterior strut widths |
| W₁ˢᵗ   | Upper interior strut width |
| W      | The lower interior strut width |
| Wₑ      | Upper tie depth which equal to 2c` |
| Wᵇ      | Lower tie depth which equal to 2c |

**Greek Symbols**

| Symbol | Definition |
|--------|------------|
| θ      | Inclined strut angle from tie |

**Abbreviations**

| Abbreviation | Description |
|--------------|-------------|
| ACI          | American code institute |
| CDB          | Continuous deep beam |
| LEP          | External support plate width |
| LIP          | Internal support plate width |
| LLP          | Width of load distributor plate |
| SDB          | Simply supported deep beam |
| STM          | Strut and tie method |