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# Survey the Behaviour of Impacted Shallow and Deep Beams

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***Abstract***

Beams under impact loading exposed to a very high strain rate attacks its energy to limits may disable the beam to take a time to across the stress into its support. At such conditions, beams has to be designed to such impacts which occurs usually by accidents. Design is difficult without understanding the response and behaviour of beam under such conditions. This paper surveys the studies for shallow and deep beams exposed to dropping weights and certain that, the concrete beams response depend on many factors like: longitudinal reinforcement, dropping weight velocity, and beam stiffness. For over reinforcement steel bars or high longitudinal steel reinforcement, the behaviour of beams tends to shear failure. Beams resist impacts almost by its inertia and little resistance gets from supporting. For deep beams, the governing failure is strut tie for impact and static loads. The dynamic increase factor (DIF) of deep beams depends on (a/d) ratio, longitudinal and transversal steel bars amounts and the static magnitude of deflection.

*Keywords:* Deep Beams, Shallow beams, Impact load, impacted beams.

## 1. Introduction

In accordance to ACI-318 code [1] concrete beams are divided into a shallow and deep beams. All concrete beam usually consider as shallow beams except in two cases will be considered as deep, the criterions of division into low and high beams are: the shear span to total depth less than or equal to four, and the point load applied at a distance equals doubled beam height from support. The shallow beams designed with respect to Bernoulli beam theory in which the cross sections remain plane after loading, but in deep beams it will not remain plane (Timoshenko beam theory) [2]. So, the ACI-318 code provides a strut and tie method to analyse the deep beams, in which the stress waves flow within the member in a shape of truss and classified the beam into B and D regions. Shallow beams failed by shear or even bending in dependence on the beam geometry and the ratio of main steel reinforcement and stirrups. While for deep beams diagonal shear failure usually occurs due to high bending capacity of deep beams.

Impact loads which exposed on structures resulting by vehicle collisions, terrorist attacks, falling rocks in mountain regions, industrial accidents, Explosions, pedestrian blocks, roadside barriers landslides and impulsive loads as show in (Fig.1)[3–9]. Impacts cause a large inertial force which will accelerate the member. If the member was ductile, the acceleration can be ignored because the failure happened after member accelerated and the oscillations inertia fades away [10].

Impact load capacity usually higher than the static loading capacity of brittle beams. The impact load applied usually on a very small region, sometimes concentrates in a point (in case of spherical shape impactor), this concentrate causes a palling, punching, or maybe drilling [14]. The impact region is an area where the impactor inertia released on and the failure becomes worse when the impacted region is small [15].


**Fig. 1.** Some types of impacts by structural members.. a)Pedestrian bridge [11]. b) Vehicle crashes into structural member [12]. c) Rock fall over a tunnel [13].

Concrete structures response under impact load differs from static one due to two reasons, firstly, the wave propagation effect [4, 16], in which the stress transformation within the loaded structure differs in local and global, which caused a difference in the negative bending moment and reaction force [17–19], while the second is the stain rate effect [20, 21]. Members under impact loading exposed to a very high strain rate loading, in such matter, the structure responses to the load rapidly from zero to peak external stress applied. The internal work develops also rapidly to balance the external one [22]. There are many ways to test concrete under high strain rate like, free fall bodies, explosive tests, hopkinsins' split bar test, charpy/ Izod test and fracture machines tests [22].

Impact load measured using direct and indirect methods. The direct method done by instillation a load cell at the impact point, while the indirect method confined by getting the impact force by measuring the acceleration and convert it to force by multiplying it by the mass [23].

The impact load accelerates the beam and attack its' inertia force [24, 25]. Due to beam large acceleration under the impact load, its inertial force has the most significant

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effect under dynamic loadings [26] especially in the first milliseconds of impacting when the beam resist the hit by its inertia only and before reaching the load to support [27, 28]. Ignoring inertial force leads to an error in calculating reinforced concrete beam fracture if designers equals the exposed impact load to the bending load carried by beam [29]. The structural response of the member depends on some parameters like impact energy, the member stiffness, contact rigidity, and material mechanical properties [14, 30–33]. In laboratories, it can be provide an impact load easily using several methods –as a branch of dropping bodies- like: dropping weight, swimming pendulum and rotating flywheel. Dropping weight classifies into a single blow, repeated blow with a constant value and repeated blows with an increment magnitude. There is no effect for the striking face of steel impactor on the dynamic response [34]. The article surveys the past researches for the importance of this subject and its novelty. The study involved shallow beams and deep beams under the effect of impact loadings.

## 2. Shallow beam behaviour under impact loads

Generally, the shallow beam reaches the peak impact force after 1 milliseconds (ms) and the overall impact period hold within 10 ms only for low impacting velocities [28, 35–37]. For higher ones, the duration may become 6 times the slow impacts [37]. The peak point of impact load occurs at the time of zero deflection, as concluded by N. Kishi et al. [37], it is mean that, the beam has no enough time to deflect because of the too high impact velocity, so it reaches its peak impact load with no time to be deflect.

When a stress wave generates due to impact load, the wave flows inside the concrete shallow beam till reach to its surface at sides (near support) then the wave reflect back as a tensile stress. When the stress wave arrived at the free surface of the beams at the side, it was reflected as a tensile stress wave. The generated compressive stress wave intersect with the reflected tensile one, that will minimizing the compressive stress wave and increases the tensile amplitude. The concrete beam may be cracked due to this tensile stress. This process may be repeated until the resultant stress wave becomes lower than the dynamic tensile concrete strength [28, 38].

Dynamic loads especially impulsive ones, transported within the member by stress wave separation into the solid body particles vertically and laterally. So, every discontinuity in beam (caused by opens and shear or flexural cracks) obstructs the stress wave and the vibrations to extent the support beam side. This matter cause weakens in receiving all real response data at support during failing objects impact experimentally tests [39].

Shallow beams which exposed to statically one point load show only a positive flexural cracks under loading point, while for impact ones, negative and positive moment cracks also generated. The negative ones appears at the top surface of beam besides supports [40, 41] as shown in (Fig.2).

**Fig. 2.** Cracked beam due to an impact load [40].

Researchers classified into three opinions when discussing the reason behind these cracks. The first, It is due to the beam local negative curvature resulting in tensile strength [42]. The second, it is due to supporting conditions (i.e. the upper roller support which is very essential to prevent the beam from uplifting)[4]. While the third, said it is due to beam hogging [43].

Furthermore, when the inertial force is greater than the impact force, the support reactions are downward to arrive at force equilibrium, shear and moment diagram differs compacting with the static point load as explained in Fig.3. It can be also noticing that, the impacted beam exposed to negative moment as a result of hogging due to the inertial force of beam [43].

Peak impact force can be calculated by an empirical equations concluded from other researchers [44–46]. Like Eq.1, Eq.2 and Eq.3.

$$F_{dp} = \left(12.6\, v_0 - 0.0079 v_0^3\right) * 9.8 \quad (1)$$

$$F_{dp} = 980\sqrt{\frac{m_2}{1000}} * \frac{v_0}{8} \quad (2)$$

$$F_{dp} = 880\sqrt{\frac{m_2}{1000}} * (\frac{v_0}{8})^{\frac{2}{3}} \quad (3)$$

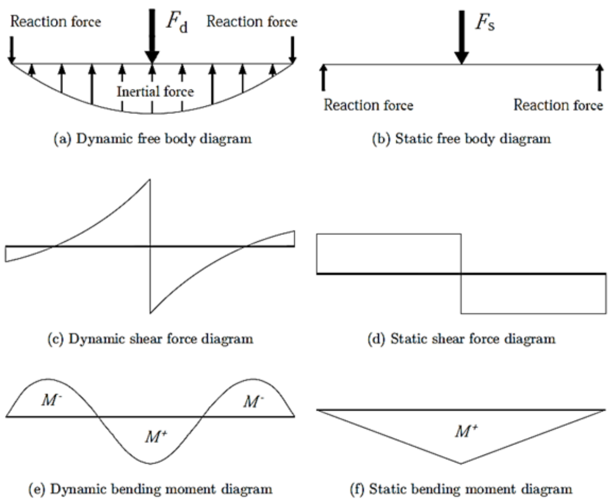


**Fig. 3.** Shear force and bending moment diagrams for static and impacted simply supported beams [43].

From the equations above, it's clear to notice that, concrete beam mass has no effect on the peak impact force, but Guo [25] offers an opposite opinion explained in Eq.4.

$$F_{dp} = (52.5 v_0 + 30.8)(0.19 \ln\left(\frac{m_2}{m_1}\right) + 1) \quad (4)$$

Where $\frac{m_2}{m_1}$ are impactor mass to beam mass, and $v_0$ is impactor velocity.

The impact load resisted by supporting and beam inertia [35]. It can be noting that[36], only 17.5% of the impact load reached to the support and the remain 82.5% resisted by beam inertia. This percent is not general but depends on concrete beam inertia properties. From Fig.4, its can be noting that, the beam in the first phase (transient load) resist impact load by its inertia only while for the second phase (free vibration) the reactions accompanied slightly.

To design the beam to impact load, the maximum deflection value under impact Δ_max has to be calculated. Generally, impacted beam may be design as static load with amplification factor n, static displacement has to be indicated under the same weight, thereby finding the maximum stress and displacement from the Eq.5 formula [47]:

$$\Delta_{max} = \Delta * n = \Delta * \left[1 + \sqrt{1 + \frac{2h\eta}{\Delta}}\right] \quad (5)$$

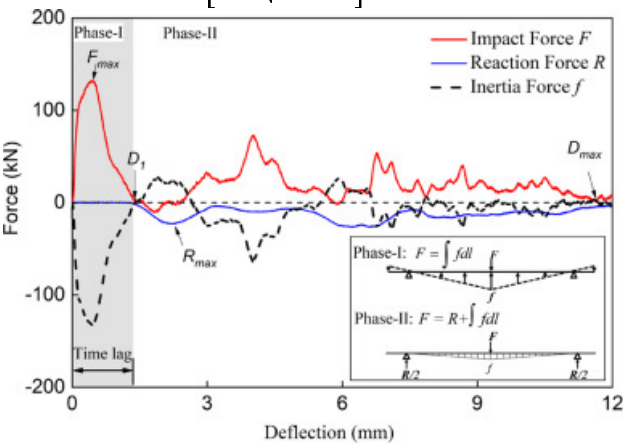


**Fig. 4.** Forced and free vibration periods for beam resist impact by inertia and supporting [48].

Where $\eta$ is the efficiency of the kinetic energy converting the moving mass, equals 1 for collision 100% efficient. If h=0 then n=2. If the mass travels horizontally then n calculated from Eq.6, while the stress is calculated from Eq.7.

$$n = \sqrt{\frac{\eta v^2}{g\Delta}} \quad (6)$$

$$\sigma_{max} = \frac{w * L * c}{4 * I} \quad (7)$$

Where $g$ and $\Delta$ are the gravity acceleration and static deflection respectively, w is the impactor weight, h is the dropping height, L is the beam length, I moment of inertia of beam and c equals half the beam height.

Kishi et al [37] discovered that, the impact shear capacity of RC beam without shear stirrups equals 1.5 the static one. During impacting, the beam deflects downward and getting away from the dropping weight (i.e. Impactor), which will leads to impact force decreasing due to descends of interaction between the beam and impactor, then impactor rebounds and contact disappear.

Generally, it can be concluded from the past researches [27, 28, 35, 37, 48] that, the crack behaviour of shallow beam under impact load classified into three categories in accordance to dropping weight velocity. Firstly, if the velocity was relatively low, the concrete beam failed in flexural bending cracks, in another word, the slow drop weight acts as static load. This response appears also in [5, 39, 42, 44]. Flexural crack width depends also on the impactor velocity [37, 39]. The crack width does not affected by the subsequent blows [27]. The beam collapse due to bending when the residual displacement reaches 1.1% of the clear span length [49].

Secondly, diagonal shear failure occurred at high velocity rate, and shear plug ,at higher, impactor velocities [50]. Diagonal collapse happens in beam exactly under the impact force point in a very short direction. This ball shape collapse may occurs also under low velocities of dropping weight if the magnitude of transversal reinforcement increased [27]. The philosophy of shear plug can be explained as the following: when the dropping weight hits the beam, the travelling stress passes through the beam at a velocity equals v. Immediately at the first split second of impact, an infinitesimally small section at the center of the beam will accelerate corresponding to the applied velocity [51]. The neighboring sections stills at rest. Duwez et al. [52] illustrated that, the bottom of the V there is a stationary one plastic hinge, while at the top there are two moving plastic hinge travelling away from the V centre, which will effects on the shear plug enlarging. The velocity of the central portion decreases as the hinges move outwards, bringing the rest of the beam into motion. When the bending moment transmitted across the moving hinges drops below the yield moment, the two moving hinges stop travelling and cease to exist. From then on, the beam is essentially folding about the central hinge and continues to do so until all the kinetic energy has been absorbed.

The third shape occurred in relatively high speed impactor, in which the cracks start diagonally then become parallel to the main longitudinal bars. The latter may expand or short in accordance to speed. The RC beams collapsed under shear failure due to the flexural cracks connecting [37].

Zhao et al. [35] (Fig. 5) shows typically experimental beams under shear and flexural and shear failures. For the same beam geometry, the static load causes a bending cracks while the dropping weight causes shear-flexural crack as explain in (Fig.6) [52,53]. It is worth to mention that, if the high ratio longitudinal reinforcement bars forced the beam to fail in shear even when the velocity was low [5, 28]. On context, the little or no shear reinforcement cause to converting the behavior of low velocity impacted shallow beam from flexural behavior to shear plug (bell shaped form [38]) [27].

**Fig. 5.** Beams crack under impact load [34].


**Fig.6.** Difference in crack pattern between static and impact loads [53].

Fu et al. [48] provides an indication for the high and low speed classification, the impactor velocity between 6.9 and 8.4 m/s is a critical speed converts the beams behaviour from flexural to shear, but the behaviour does not depend on the velocity only, so these numbers cannot be generalized. Adhikary et al. [54] suggested that, the slow loading rate equals 0.04 m/s, medium 0.4 m/s and the high one equals 2 m/s.

Kishi et al. [37] suggested that, when the shear-capacity ratio (static shear capacity/static bending capacity) is less than one, the shear behaviour currents in beam. In contrast, if the ratio is larger than one, the flexural behaviour shown but conditioned by the drop weight velocity.

Impacting velocity has another significant effect on shallow beams which is bended span length $L_{effective}$. When the velocity is slow, the beam completely has the enough time to resist the load and bend, while for higher velocities (but still within the flexural failure) the bended span minimized till reach a small part below the impact point. Regarding to that, the concrete beam deflection under high drop velocities has less effected by the beam span than the flexural beams failure [35]. This behaviour could be understanding from reference [21]. Due to this behaviour, the support condition changes from hinge to both ends fixed.

Time lag or time delay (which is the delay of responding the support to the applied weight) have to be measured by researchers to get an indication for stress wave propagation influence [35]. It is seems to be related only on the beam span [35]. The reason behind time delay expressed in reference [36], beam initial rising period amplitude is very small to provide the sufficient deformation, that will lead to generate a variations in the contact resistance, and therefore, the signal off the reaction load disappears a sensible vibrations. 1 ms has been indicated for time lag for Fujikake's [5] beams.

A phenomenon observed in past researches worth to be mentioned and discussed, which is the amount of reaction load at high velocity impactor is smaller than the lower one. This phenomenon may be generated due to two reasons [38]:

1. The damaged beam associated with the cracking of concrete and steel yielding due to stress wave absorption.
2. The short duration of loading process and time delay.

Few researches investigate the hogging occurs in concrete beam during impact hit. Hogging moment changes the expected mechanism of cracked beam [27, 38]. The peak value of hogging is proportional linearly with the impactor force [25]. Hogging moment for simply supported beam can be calculated from the Eq.8 [25].

$$\left|M_p^-\right| = 0.12\, F_{dp} + 6.84 \tag{8}$$

Where $F_{dp}$ represents the peak impact force.

The impact energy is reflected back into the rebound in an ideally elastic impact while a portion of the impact energy is transformed in elastic deformation and remaining part of the impact energy is consumed in the plastic deformation and failure in real impacts [55]. The energy balanced method can be used to verify the input kinetic energy and the component energies in a beam. The energy-balanced eq can be expressed as Eq.9.

$$\tfrac{1}{2}M(V_1^2 - V_2^2) = E_b + E_s + E_m + E_c + E_k \tag{9}$$

where M is the dropping weight mass, V1 and V2 are the initial/residual impactor velocity, $E_b$, $E_m$, $E_s$, $E_c$ represent the energy in the form of bending deformation, membrane component, shear deformation, and indentation effect when the projectile rebounds from the beam, respectively, and $E_k$ is the beam kinetic energy. Studies like [56–58] matched well with this theory.

The concrete beam after impact hit, loss some of its ductility due to the impact cracks. The magnitude of losing depends on the impactor energy. Dok et al. [39] found that, for low impact weight the beam lost 24.6%, for medium weight it lost 31.9% and for higher one 44%.

The absorbed energy of impacted beam increases with dropping weight velocity increment irrespective to beam type [37]. The deformation energy $W$ of simply supported beams may calculated by an equation offered by reference [5] so as the energy loss during impact $E_R$ (Eq.10 and Eq.11):

$$\frac{m_2 v_{ib}^2}{2} - E_R + (m_1 + m_2) g \delta_{max} = W \tag{10}$$

$$E_R = \frac{m_1 m_2}{2(m_1 + m_2)} v_{ib}^2 \tag{11}$$

Where: $m_1$ is the equivalent mass of beams, $m_2$ weight of impactor, g is the gravity acceleration, $\delta_{max}$ is the maximum static load of beam, and $v_{ib}$ impactor velocity. The experimental results of Zhao et al [35] where verified with the pervious equations. It has been found that, for flexural behaviour beams, there were 10% underestimated caused by neglecting deformation energy strain. While for shear behaviour beams, a large difference observed reached even to 100% because of the difference between the estimated failure shape and the actual displayed one.

## 2.1. Impact force history

The generated shape of impact load – displacement curve is approximately triangular, as well as the reaction – deflection one. A second peak appears in impact history resulting from steel reinforcement re-bearing after the concrete cracked [37], but it may occurs also due to the impactor reflect after first hit (Zhao et al [35] explained the multi peaks for the same reason) , which will cause another hit per single drop (as shown in Fig.7 and Fig.8).

The triangular shape of impact load force versus time curve has been appeared at the numerical model proposed by [50] and the experimental test of (36). The analytical solutions are better from experimental ones to get the exact triangle and the overall behaviour [38, 50].

The higher impact load leads also to higher plastic deformation capacity as a result of the positive effect of the diagonal shear cracks near the impacting point. Thus, a large part of steel reinforcement may reach to the yielding point, consequently, the length of plastic hinge increases and the plastic hinge gets larger [42].

Impacted structures behaves in two phases, firstly, the impact load phase which holds just few milliseconds (10ms) and the free-vibration phase which may reaches to 100 ms [28].

The beam under impact load has two shapes of displacement depends on the dropping weight velocity, the first is a wave fluctuates faintly accompanying by drift after the impact loads drops to zero. This phenomenon means that, the main steel bars only resist the impact force (free vibration period) after diagonal cracks growth [37]. The second is for faster impactor velocities, the deflection wave rises from zero then moves within a constant value (see Fig.8). Impactor velocity effects on the beam deflection, where the deflection minimized when applying a high loading velocity because the time required to reach the peak displacement minimized [35].

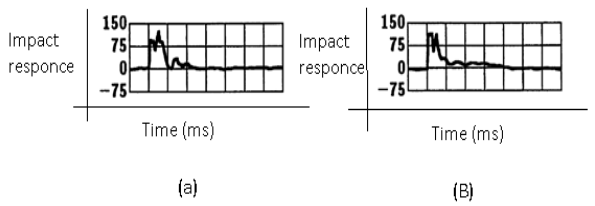


**Fig. 7.** Load - Time impact wave (A. at 3m/s impactor velocity and B. at 5m/s dropping velocity) [37].

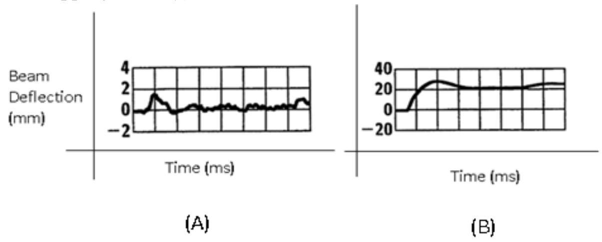


**Fig. 8.** Deflection- Time wave of beam under dropping weight (A and B are at 3&5 m/s impactor velocity respectively) [37].

## 3. Deep beams under impact loads

The shallow beam behaviour may develop from flexural to shear when supplying the impact load nearby the support which may satisfy the second condition of deep beam specification in ACI- code (the impact weight applied at a distance equals 2h from support) [39].

As mentioned previously, failure mode of statically loading deep beams is always shear failure, for deep beams, it has been noticed that, for impact load and for any loading rate, the shear failure dominates usually, the failure under impact load occurs also at strut as crashing (as shown in Fig.9). Strut crashing combined with diagonal splitting for low impactor velocity, bearing at medium speed, and massive spalling of concrete at high impact loading rate [54].

ACI- code 318 provides an equation to calculate shear resistance strut without shear reinforcement but there is no guidelines for those with strips (1). The shear reinforcement enhanced deep beam capacity by 25% of equation A-4 in ACI 318-14 code. It has been found that from reference [54] increasing shear reinforcement caused to incrementing the ultimate shear resistance of beam for low, medium and high straining rate. The load versus deflection curves of deep beams under (low, medium and high) impacts has a delay indentation before reaching the peak value due to cracking development. Beams (without shear stirrups) stiffness increases when raising loading rate and the existence of shear reinforcement has no effect on stiffness [54]. Yielding stress of ties rises when increasing loading rate.

If the ultimate shear strength of deep beams is little (due to no or few transversal reinforcement) so as longitudinal reinforcement rate, the increment of ultimate load carrying capacity is higher when comparing with deep beams has high amount of main reinforcement [54].

There is a mathematical model to calculate DIF (dynamic increase factor) suggested in reference [54] for impact load depending on (a/d) ratio and it gets a good accuracy with its experimental work for static, low, medium and high loading rates as shown in Fig.10.

The empirical equation of DIF factor of deep beams without stirrups is given below at Eq.12

$$DIF = \left[0.45 + 0.09\rho_g + 0.48\left(\frac{a}{d}\right)\right] e^{\left[0.3-0.05\rho_g-0.05\left(\frac{a}{d}\right)\right]\delta} \quad (12)$$

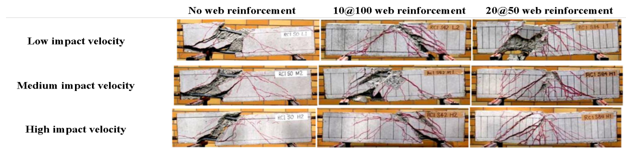


**Fig. 9.** Strut failure of impacted deep beams [54].

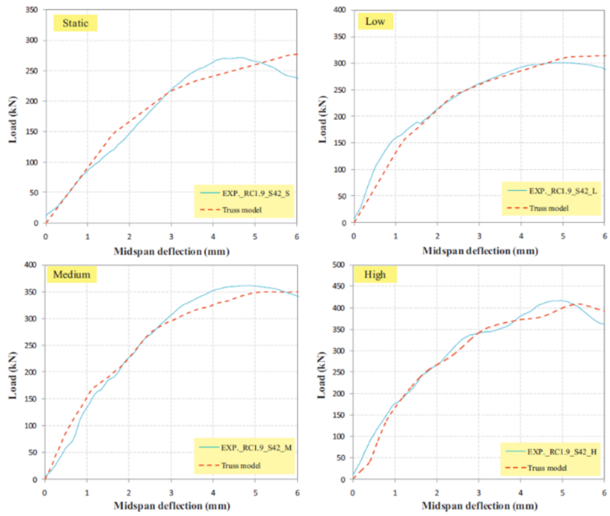


**Fig. 10.** Truss model results versus experimental lab data [54].

If the deep beam has a transversal reinforcement then the DIF equals:

$$DIF = \left[1.25 - 0.04\rho_g - 0.04\rho_v + 0.05\left(\frac{a}{d}\right)\right] \cdot e^{\left[0.22-0.03\rho_g-0.03\rho_v+0.03\left(\frac{a}{d}\right)\right]\delta} \quad (13)$$

Where $\rho_g$ and $\rho_v$ are main and shear steel reinforcement percentages, $\left(\frac{a}{d}\right)$ is the shear to span depth and $\delta$ is the static deflection.

## 4. Improve concrete properties against dynamic loads

In order to earning concrete a dynamic properties enhancement, it has to provide a better energy absorption to the mix. It has been found from past researches [14, 22, 59] that, the dynamic properties of concrete improved by adding steel fiber to the mix. The steel fiber works on reducing micro cracks growth by making connections between cracks edges [60]. Adding fibers not to increase the strength against impacts only but to increase ductility [22]. Another way to improve the concrete energy absorption is by replacing rubber by a specific percentages of aggregate (even sand or gravel). The generated mix (rubcrete) has a special improvement energy absorption [61–66] (higher impact energy by 10-18% for 15-30% rubber content [28]) but a lower mechanical properties due to replacement [67–70]. Rubberized concrete has more energy absorption than steel fiber concrete but lower compressive strength [59], concrete compressive strength can be improved by adding steel fiber or any other cementitious filler material or even by adding more steel reinforcement in compression zone. Beams shear resistance under impact load become more critical due to rubber [28], so the rubberized deep beams must be designed in accordance to the governing failure, shear.

Rubber in concrete mixes behaves like a small impeded springs working on energy absorption. So, it has been evident that, for 15% and 30% rubber replacement leads to reduce stress wave velocity by 5% and 26% respectively [28].

Fiber reinforced polymer (FRP) has been used also to improve the flexural, shear and impact resistance of concrete beams [17, 19, 71, 72]. It has been found that, several drops led to damage the concrete beams, reached to 30 drops. Since every single drop cause a vibration waves exposes the top surface of beam to tensile and the bottom to compressive stresses, and that cause a cycles of tensile and compressive waves at top and bottom. The existence of FRP will combine the top and bottom surfaces of beam and during the first drops, flexural cracks formed at bottom. After several drops, shear cracks start to form due to crack matching until reach to the final failure drop. It has been found that, using FRP allows the beam to ingest more drops [71]. Using stiffer FRP can enhance capacities of RC beams under impact loading [72]. Using FRP U-wraps is highly recommended to maximize the capability of longitudinal FRP strips [73].

## 5. Conclusions

The overall duration of impact is 10 ms and its peak is 1 ms for low velocities, while for high velocities, it may multiplied by 6 times.

In accordance to impact velocity, the beam (or a part of beam) response to the impact hit. If the velocity is low, the overall beam response to the hit and bend due to it, while for high impacts, a point of impact collapsed by ball shape failure.

Shallow beams failure mode depends on: steel main reinforcement, Shear stirrups, and velocity of impactor.

Most of the impact energy resisted by beam inertia and few amount of it withstanded by supporting. This is due to the fast of stress wave.

The impact shear capacity of RC beam without shear rebar equals 1.5 the static one.

Shear failure dominates the deep beam mechanism in static and impact loads. The velocity of impactor roles the minor accompanying other failures.

DIF factor of deep beams depends on (a/d) ratio, longitudinal and transversal steel bars amounts and the static magnitude of deflection.

All methods of improving concrete compressive strength will be benefit to enhance structural member resistance to impacts, while adding rubbers weaken the compressive strength but provide a members with a higher energy absorption.



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