Review of Concrete Structures Strengthened with FRP against Impact Loading

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Abstract

Recent global terrorism activities and threats imposed prominent danger to the public civil infrastructure, and thus blast and impact resistance design of structures has become an indispensable requirement in the design processes. Fiber reinforced polymer (FRP) can be used as an excellent material to improve the blast and impact resistance of structures. Up to now most studies concentrate on blast-resistance of FRP strengthened structures. The number of studies about impact resistance of structures strengthened with FRP is very limited and the findings in these studies are controversial. Since structures under blast and impact loadings do not necessarily behave the same, it also is important to understand the performance of FRP strengthened structures subjected to impact loads. This study aims to provide an overview of the impact resistance of structures strengthened with FRP, which include reinforced concrete (RC) beams, RC slabs, RC columns and masonry walls. This study also reviews the dynamic properties of FRP materials. Although some issues still need to be investigated and clarified, it would be suggested that FRP can be used to strengthen and protect structures against impact events or terrorism activities.

Keywords: Fiber Reinforced Polymer; Impact loading; Strengthening; Retrofitting.

Introduction

Recent global terrorism activities and threats imposed prominent danger to the public civil infrastructure, and thus blast and impact resistance design of structures have increasingly attracted the research community. Fiber reinforced polymer (FRP) has been commonly used in the field of civil engineering for a few decades [1-4]. This material can be utilized in improving the blast and impact resistance of structures. It has been used in strengthening or retrofitting existing structures, or building new structures ranging from beams, slabs, columns, to walls [5-14]. The use of FRP has been shown to increase the strength, stiffness, and ductility of strengthened structures. This use has now become popular worldwide because of the superior properties of FRP materials, which have high strength to weight ratios and excellent corrosion resistance. The behavior of structures strengthened with FRP under static loads has been comprehensively studied and presented in the literature [15-17]. However, studies about dynamic responses of structures strengthened with FRP are relatively limited. In terms of dynamic resistance, more attentions have been paid to these structures against blast loading rather than impact loading [18]. Accordingly, Buchan and Chen [18] presented a state-of-the-art review of blast resistance of FRP materials strengthened concrete and masonry structures. Studies of FRP strengthened structures against impact loadings are very limited. As a result, there is no review study about impact resistance of concrete and masonry structures strengthened with FRP either. Experiences and research findings of FRP structure performance under blast load may not necessarily be applied to assess the structure performance under impact loads. This is because the effects of impact loads on structures are different from those of blast loads owing to the different loading rates and loading type (distributed or point loads). Blast loads have very high loading rates (~10^3 s^{-1}) and are usually distributed in part or entire structural component while impact loads usually have relatively lower loading rates (~10^1 s^{-1}) and are often concentrate point loads on structures. These discrepancies result in differences of structural behaviors under blast or impact loads. It is thus necessary to investigate the impact resistance of these structures in order to provide a better understanding of these structures against all loading conditions.

It is worth noting that impact loading conditions on structures can be induced by vehicle impact, ship impact, airplane impact, rock-fall impact, windborne debris impact or missile impact, etc. The main concern of the structural performance under impact loading is not only about the structures' strength to resist the impact load but also their energy absorption capacity. In such cases, the size and mass of the impactor, as well as the impact velocity, are very important. An impactor with a large mass but low velocity and another one with a small mass but high velocity have very different effect on structures although they may have the same kinetic energy. Besides the impactor, the response of the structure also depends on the structural mass itself. There are in general three separate situations: (1) a very large object struck by a small impactor, (2) an object with comparable mass as the impactor hit on it, and (3) a small object struck by a large impactor [19]. While the third case is relatively rare, the other cases are often encountered. In the first case, such as shooting a bullet on a structure, a local damage can be expected at the contact zone. This case has been comprehensively studied and thus solutions have been suggested in the form of empirical formulae. However, in the case of impact between two comparable masses such as vehicle and rock fall impact on a structure, which are the main concern in civil engineering, is still unclear [19].

Accidental impact loads such as vehicle and ship impact are common and some studies in the literature investigated the measures to strengthen structures against such impact loads [20-24]. This study presents a review of impact resistance of concrete and masonry structures strengthened with FRP in such cases. It includes a brief introduction about impact testing methods and dynamic properties of FRP. More comprehensive discussions and analyses about impact resistances of FRP strengthened concrete structures will be presented accordingly. It should be noted that studies about this topic are still extremely limited. Most of relevant references available in the literature have been collected and discussed in this review study, which summarizes state-of-the-art understanding of this important topic. Discussions and recommendations for further studies are also provided.

Impact Testing Methods and FRP Composites

Impact Testing Methods

Impact testing methods should be designed to ideally simulate the loading conditions to which a structure is subjected in operational services and reproduce failure modes and mechanisms likely to occur. Generally, the impact testing methods can be divided into two separate types: low velocity impact by a large mass (drop-weight tests or pendulum) and high velocity impact by a small mass (runway debris or small arms fire) [25]. The more common methods are low velocity impact by a large mass. These methods include Charpy and Izod pendulums, hydraulic test machines, and drop-weight tests (Fig. 1), which are designed to deliver velocities up to about 10 m/s. The Charpy and Izod pendulums tests suffer a number of disadvantages, for example the load-time curves often contain high frequency harmonic oscillations caused by the natural response of the impactor [25]. Even though these effects can be filtered as the harmonic frequencies of the various components have been determined, they yield difficulties for researchers [26]. In addition, many specimens used in these tests are short and thick beams and are not thus typical of structural components in the civil engineering discipline.

An impact test can be conducted by dropping a weight onto test specimens from a certain height. Generally, the impact event does not cause complete destruction of the test specimens but rebounds. The incident velocity of the impactor can be theoretically estimated by the equations of motion or experimentally determined by a high-speed camera, accelerometer, or an optical sensor. One of the advantages of this type of tests compared to Charpy and Izod pendulums is that a broader range of test geometries can be adopted. Although a semi-spherical impactor is commonly used in these tests, the use of other shapes such as cylinders or sharp point is possible. Dynamic capacities of the specimens can be determined by one-blow drop-weight test while fracture energy is determined by multi-blow tests in which the specimens fail by a number of drops [27].

Potential Materials

There are many types of FRP and polymer materials available for strengthening and retrofitting concrete structures. An appropriate selection of the most suitable material is based on the optimal performance and cost. The most popular materials used are glass fiber reinforced polymer (GFRP) and carbon fiber reinforced polymer (CFRP). In general, GFRP is more economical than CFRP but the later can provide higher tensile strength and stiffness. Accordingly, high strength CFRP material can save resin and may lead to a more economic total solution [18].

Crawford et al. [28] recommended the use of aramid FRP (AFRP) for strengthening structures in terms of impact events due to its impact resistance rather than CFRP and GFRP. However, in terms of confinement effect, Crawford et al. [29] suggested that CFRP is preferred to GFRP and AFRP for wrapping columns because it possesses high stiffness which prevents the concrete from expanding.

Davidson et al. [30] thoroughly described the process of selecting a retrofit material. Twenty one potential materials were evaluated in the initial phases of their tests: seven of those were extruded thermoplastic materials, thirteen of them were spray-on materials, and one was a brush-on material. All those materials were ultraviolet and temperature stable, flame resistant and could be acquired at an acceptable cost. Among these materials, the extruded thermoplastics were the strongest and stiffest but they were eliminated because of their difficulty in construction. The brush-on material was discarded because it was weak, brittle and had long cure time. The spray-on materials were the most suitable in this case although they have some disadvantages.

In brief, there is no best suitable material for a particular strengthening method or a structure. A comparison between the materials is very difficult due to the variation in structures and lack of a standard for the impact testing. The impact resistance of structures strengthened with different types of FRP needs to be investigated in terms of the load-carrying capacity and energy absorption.

Strengthening Solutions

Strengthening solutions range from repair of damaged structures in order to restore their original strengths to an addition of elements to increase their capacities. Strengthening with FRP composites can be applied to various types of structures consisting of beams, columns, slabs, and walls. According to the member type, the objectives of strengthening might be one or a combination of the followings: (1) increase axial, flexural or shear load capacities, (2) improve ductility for seismic performance, (3) increase stiffness and/or (4) improve durability against environmental effects [31].

The study by the Concrete Society [16] summarized the most common traditional techniques for strengthening structures. Firstly, high tensile strength FRP materials bonding the tensile surface of structures can be utilized to enhance flexural resistance in beams, slabs or walls.

The FRP materials in such cases can be laminates, sheets, plates, or reinforcing bars (near-surface-mounted method). Secondly, capacities of compression members can be improved by adding FRP materials in order to provide confinement of the concrete, in which FRP sheets are commonly used to wrap around the perimeter of the members. Lastly, FRP strips made of laminates or sheets may be used to bond to the sides of beams in order to enhance their shear resistance. These strengthening techniques and FRP materials have been thoroughly studied in terms of static loads rather than dynamic loads. The dynamic behaviors of strengthened structures and FRP composites are relatively limited, which are summarized and discussed in the following sections.

Dynamic Properties of FRP

Introduction

It is commonly accepted that as the strain rate increases, there is less time for damage to develop so that the amount of accumulated damage at a particular strain level reduces and then the material can sustain higher load and failure strain. The dynamic properties of FRP, i.e., strength, elastic modulus and failure strain, thus were found to be greater than those under static loading [32-35]. These studies concluded that the dynamic properties of FRP are affected by the loading rates so that they are rate-dependent. There are three common levels of testing rate: quasi-static (~10^{-5} s^{-1}), intermediate (10^{-2} - 10^{0} s^{-1}) and high rate (10^{2} - 10^{3} s^{-1}). However, some other studies in the literature observed that FRP did not show rate-dependent behavior for its tensile strength, modulus, or failure strain [36, 37]. Those studies are defined as the non-rate-dependent group. Discussions of the inconsistencies can be found elsewhere in the study [38]. The inconsistencies may be resulted from testing apparatuses, the range of the loading rate, errors in testing, and different material fabrication. A review thus is needed to discuss and clarify the inconsistent observations by different researchers.

Testing methods

Based on the range of the strain rate, some experimental methods can be utilized to test dynamic material properties of FRP, for instance, tensile split Hopkinson bar [35, 39-42], drop-weight tests [36], pendulum [43], Charpy pendulum [44, 45], Izod impact testing [46], servo-hydraulic testing apparatus [34], and explosively driven hammers [32]. Among these methods, the most popular testing apparatus for dynamic tensile properties of FRP is tensile split Hopkinson bar (TSHB) [33]. The equilibrium requirements of dynamic tests limit the specimen size [40]. Rodriguez et al. [40] have conducted some experimental tests to study the size effects and concluded that with a small size of specimens, which were carefully described in their study, the tests can provide reliable results within the natural scattering of the experimental data.

In addition to the strain measurement, an extensometer is advisable and it provides a very accurate measurement of strain in static tests. However, in dynamic tests carried out in the Hopkinson bars, the use of extensometers leads to changes in the inertia of specimens and limits frequency response of this system. Strain gauges thus are recommended in dynamic tests [40].

Effect of the strain rate on the dynamic tensile strength

It is commonly agreed that the tensile properties of FRP generally increase when the loading rate increases [40, 47-49]. The tensile properties of FRP are referred as the tensile strength, the failure strain and the modulus. It is worth noting that the word "*modulus*" is used instead of elastic modulus as usual because some studies had shown that the stress-strain curves of FRP is nonlinear [39, 40]. Studies belonging to the rate-dependent group concluded that the tensile strength of FRP increases from the static values when the strain rate is greater than about 10^2 - 10^3 s^{-1}. Only a few studies reported testing results on dynamic material properties of FRP at different strain rates. These studies are summarized in Table 1. The available testing data on tensile strength with respect to strain rates are plotted in Fig. 2.

Majority of studies had agreed that an increase in the strain rate results in an increase in the dynamic tensile strength of FRP except two studies [37, 45]. Hayes and Adams [45] observed a decrease of the dynamic tensile strength as the strain rate increases. In addition, experimental results reported by Hayes and Adams [45] showed a scattered distribution. The reason for this controversial finding may be resulted from an imperfect design of the specimen tabs since debonding at the tabs had been found during their tests. This debonding could lead to non-uniform tensile stress and thus stress concentration on more elongated fibers. Accordingly, specimens could fail at a lower load than that in static tests. Some studies are briefly summarized below for better assessments and understanding.

Rodriguez et al. [40] conducted experimental tests to investigate effects of the strain rate on the mechanical properties of aramid and polyethylene woven fabric composites. The tests were implemented by a tensile split Hopkinson bar and conventional testing machines. The strain rates achieved were 10^{-3}, 1, and 10^3 s^{-1}. The authors reported that the tensile strength increased (approximately 60%) continuously with strain rate. Barre et al. [50] also observed an increase in the dynamic tensile strength up to 50% at the strain rate greater than 1 s^{-1}. Shokrieh and Omidi [34] carried out dynamic tensile tests at the strain rate ranging between 10^{-2} and 10^2 s^{-1}. The experimental results showed that increasing the strain rate leads to significant enhancement of the tensile strength of FRP (up to 52%). In order to visualize the effect of the strain rate on the dynamic tensile strength of FRP, available data given in [34, 35, 40, 50] are plotted in Fig. 2, which shows that the strain rate significantly affects the tensile strength at the rate greater than about 1 s^{-1}. Therefore, a conclusion of the rate-dependent tensile strength of FRP in dynamic loading can be made.

Effect of the strain rate on the dynamic failure strain and stress-strain curves

Effect of the strain rate on the dynamic failure strain of FRP is questionable. Among fourteen studies summarized in Table 1, six studies did not report the failure strain [41, 45, 49-51]; Four studies found an increase in the failure strain [32-35]; Three other studies observed a decrease in the failure strain [38-40]; and only one study reported the failure strain unchanged [36]. There is thus no convincing conclusion can be made for the failure strain of FRP in dynamic testing. Accordingly, Kimura et al. [47] suggested that the failure strain of FRP are independent on the strain rate. Interestingly, Jadhav et al. [48] reported a different phenomenon from all others. This study observed that the stress and strain of FRP generally increase with an increase in the strain rate. However, the stress remained constant with further increase in the strain rate after achieving a certain maximum value of the ultimate stress while the ultimate strain increased continuously with the strain rate. The same findings were also found in the study by Hou et al. [35].

It is well known that stress-strain curves of FRP are almost linear elastic [32-34, 36, 41, 50]. However, a few stress-strain curves reported by previous studies [35, 38-40, 49] showed nonlinear behaviors rather than a linear behavior as usual. It can be seen from the literature that up to the intermediate strain rate (1 s^{-1}) it has no or insignificant effects on the stress-strain curves. On the contrary, the high strain rate (greater than 10^2 s^{-1}) does affect the stress-strain curves at which it changes the behavior of FRP from linear to nonlinear.

Discussions and Future Challenges

The complex interaction occurring between the fibers and the matrix results in difficulties in assessing the rate dependency of the constituent phases [52]. This type of complex behavior has been observed and reported in the literature, for example, as the strain rate increases the corresponding failure modes change. It can be seen from the literature, the dynamic tensile strength is more likely to increase as the strain rate rises. Accordingly, more parametric studies are still needed to qualify the effect and derive reliable analytical models. A consensus on the strain rate effect on the dynamic failure strain and the modulus cannot be achieved from the current testing data reported in the literature. Qualitative studies are thus still in demand to clarify: (1) whether the failure strain of FRP changes at high strain rate and (2) what is the true relationship between stress and strain of FRP (linear or nonlinear).

FRP Strengthened RC Beams

Introduction

Bonding FRP materials to the tension face of a RC beam to strengthen its shear and/or flexural capacity has become a popular method in recent years. As a result, a large number of studies has been carried out to investigate the structural behaviors of strengthened beams and the possibility of this strengthening technique. Structural behavior of RC beams strengthened by this technique under static loads was relatively better understood than those under impact loads. There have been three popular methods to strengthen RC beams: (1) bond FRP sheets to concrete, (2) near surface mounted (NSM) FRP reinforcement and (3) spray FRP to concrete [53]. FRP sheet bonded directly to the soffit of beams has become a popular flexural strengthening method. Transverse FRP straps are also utilized to strengthen beams to improve their shear capacity. In the NSM method, grooves are first cut into the concrete cover of a RC beam and the FRP reinforcement is bonded in the grooves [54]. Experimental verifications and analytical studies about this method in the static discipline were quite clearly stated and presented. However, understanding of FRP-strengthened RC beams under dynamic load with high loading rates is still very limited. There are only a few studies in the literature focusing on the dynamic strength of these beams. This section presents a review of some strengthening techniques used for RC beams in the point view of dynamic responses.

The number of studies dealing with the dynamic behavior of RC beams strengthened with FRP is limited. Among these studies, the free vibration behavior and the response to impulse loads have been studied by drop-weight tests [55-57]. Meanwhile, Erki and Meier [58] conducted impact loading tests by raising up one end of the beam and dropping it on the support. In both cases, the results indicate that the use of the externally bonded FRP sheets significantly enhance the impact resistance of the strengthened RC beams and reduce their maximum deflections. However, understanding of the failure modes, the actual rupture strain of FRP sheets, and the bond mechanism between concrete and FRP is still unclear. Therefore, these issues are analyzed in the following sections.

Failure Modes

It is worth noting that, in the case of RC beams under impact loading, the shear mechanism is typically critical even these beams are flexure-critical under static loading conditions [59-61]. A similar observation was drawn in other studies [62-65]. These authors found that RC beams which failed in a ductile flexural manner under static loading shifted to a brittle (shear) failure when subjected to impact loading. Hughes and Beeby [66] recommended that shear failure may occur in RC beams due to activation of higher modes under impact loading. In addition, Ožbolt and Sharma [64] argued that under impact loads (velocity around 1 m/s) shear reinforcement has not been activated yet and thus the dynamic response is not similar to that in static loads. Pham and Hao [61] found that there is very small or zero reaction force at the time of the maximum impact force. To maintain the equilibrium condition, the shear force is equal to half of the impact force which is extremely large. The shear force thus becomes critical and lead to shear failure. This change in the structural behavior of RC beams strengthened with FRP needs to be investigated against impact loading conditions. Unfortunately, this phenomenon in RC beams strengthened with FRP has not been investigated against the impact loading conditions yet.

As experienced in static tests for beams strengthened with FRP, the main issue causing the failure of beams is FRP debonding. In the one-blow impact tests, they can provide a close form of impact events in reality but the progress of failure could not be carefully examined because the duration of the impact event is about a few milliseconds. High speed camera may be used to capture the failure mode in such cases. On the contrary, repeated impact tests do not well simulate realistic impact events but they can provide important understanding of energy absorption and progressive failure of the tested specimen. Previous studies observed that the failure of the tested beams could be initiated with either flexural cracks or shear cracks (depending on the beam designs), which led to cracks opening; and as a result they induced the peeling stress on the interface between the concrete and the FRP laminates. Finally, the specimens usually failed by debonding or rupture of FRP. This progressive failure is qualitatively similar to that under static tests. However, it should be noted that majority of the previous studies about this topic in the literature only give qualitative observations.

Erki and Meier [58] conducted tests on 8-m-long RC beams strengthened for flexure resistance. Two beams (BF1 and BF2) were strengthened with CFRP and the others with steel plates. Interestingly, the impact loads were not caused by traditional drop-weight tests. Impact loading was induced by lifting one end of a simply supported beam and dropping it. The strain rate of loading varied from an average of 0.7 s^{-1} to a maximum of over 0.84 s^{-1}. Beam BF1 was dropped from the height of 0.5 m, 1 m, and 1.5 m. After 1.5-m-drop, the beam failed by debonding of the outside laminate and then rupturing of the intermediate laminate. Meanwhile, Beam BF2 dropped from 2 m height failed by debonding and rupturing of the laminate. It can be seen that debonding of the laminate was observed in the failure of the two beams. However, since it is difficult to study the progress of the failure mechanism of FRP strengthened RC beams, the first occurrence of the debonding or the rupture of FRP was not discussed in the study.

White et al. [67] cast and tested nine 3-m RC beams under a high rate of loading, but the highest strain rate obtained was only $6.9x10^{-3}$ s^{-1}. The details of equipment and types of tests were not reported in the paper. The strain rate achieved in these tests was closer to quasi static than an impact event. The experimental results showed that all eight FRP strengthened beams failed by debonding of FRP. The strain of FRP was reported at about 6,200 με when the fiber debonded. For convenience, the debonding strain of FRP was defined as the strain of FRP when the laminate debonded.

Tang and Saadatmanesh [56] tested five RC beams, which had a cross section of 203 x 95 mm, with multiple drop-weight tests. It is noted that the number of multiple drop-weight tests in this study was up to 30 drops. The authors argued that because the impact loading causes vibration, the top and bottom faces of the beams would experience cyclic tensile and compressive stresses. FRP (carbon or Kevlar) thus was bonded to two sides of the beams. After testing, flexural cracks first occurred on the bottom face of concrete and propagated upward to the level of the neutral plane. Since the impact load increased, diagonal shear cracks was observed. These cracks extended quickly to the interface of concrete and laminate at the top or bottom and then propagated along the interface. These beams finally failed in shear. Tang and Saadatmanesh [56] bonded six strain gauges on the top and bottom faces to monitor strain of the FRP. The experimental results showed that the tension strain was larger than the compression strain at the same section. The debonding strain of FRP was about 4,000 με with the strain rate of the FRP about 1.4 s^{-1}. The lower value of the FRP strain at debonding as compared to those in static tests may be caused by stress wave propagation and multiple drops from the tests in which the damage and the FRP strain were accumulated.

Tang and Saadatmanesh [68] reported experimental tests of 27 concrete beams (203 x 95 mm cross section) under impact loading. Similarly to the previous study by the same authors, FRP (carbon or Kevlar) was bonded to two sides of the beams. A total of four types of cracks were observed: two occurred in the concrete and the other two appeared in the FRP at the bottom of the beams. Flexural cracks first occurred on the bottom face of concrete and then propagated upward to the level of the neutral plane. When the number of impacts or the height of a drop increased, these cracks extended into the interface between the FRP and the concrete. Most of the beams failed owing to shear cracks. Experimental results showed that using stiffer FRP can enhance capacities of RC beams under impact loading. Interestingly, no cracks were observed in the interface between the FRP and the concrete. The authors attached strain gauges on the composite laminates to monitor the longitudinal strain but the strain of FRP at the laminate ends was small and thus was not reported.

Pham and Hao [61] presented an experimental study on the impact resistance of FRP strengthened modified RC beams. The impact tests were conducted by using a drop-weight apparatus with the projectile weight of 203.5 kg and the drop height of 2 m. A new technique for strengthening RC beams with FRP against both static and impact loads was proposed. Its excellent performance was validated against the conventional strengthening technique. The section of the RC beams was modified to have a curved soffit before bonding with FRP. By using approximately the same amount of materials, the modified beams eliminated the stress concentration at the FRP U-wraps and provided confining pressure on the longitudinal FRP strip thus enhanced their capacities under both static and impact loads. The FRP U-wraps were found to significantly delay the debonding of the longitudinal FRP strip and thus increase the capacity of the beams. The debonding strain of FRP under impact loads was lower than that under static loads. The authors observed that locally strengthening RC beams in shear at the expected impacting area is crucial to prevent the shear failure even though the shear capacity was about four times of the flexural capacity. In addition, Pham and Hao [61] suggested that the maximum impact force and the corresponding inertial forces at the very early moment of an impact event should be used to design the impact resistance rather than the reaction forces.

Pham and Hao [60] conducted an experimental study on the impact behavior of FRP strengthened RC beams without stirrups. The RC beams were designed to have no stirrups so that the shear contribution from FRP can be properly valuated. The impact tests were conducted by using a drop-weight apparatus with the projectile weight of 203.5 kg and the drop height of 2 m. Shear deficient RC beams were strengthened with FRP by different wrapping schemes and tested under both static and impact loads. The debonding strain of FRP under impact loads was found to be slightly smaller than that under static loads. The beams strengthened with inclined FRP U-wraps yielded higher static/impact resistances than those of the beams strengthened with vertical FRP U-wraps. The authors recommended that FRP can be used to strengthen RC beams in shear against impact loads. Although the debonding strain of the FRP was smaller than that under static loads, if the actual debonding strain is taken into account, the shear contribution of the FRP can be estimated by the procedure in ACI 440.2R-08 [15].

Besides the traditional FRP, Soleimani et al. [53] conducted drop-weight tests on sprayed GFRP shear strengthened RC beams. A total of 15 RC beams (150 x 150 mm section) with/without sprayed GFRP were tested with impact velocities of 3.43 m/s or 3.96 m/s. Three strengthening schemes were investigated: sprayed FRP on 2 sides, 3 sides without anchors and 2 sides of the specimens with anchors. No sprayed GFRP fracture was observed in these tests. An increase in sprayed GFRP thickness in 3-side specimens led to increase in the specimens' capacities but it did not happen to 2-side specimens. The authors thus recommended that sprayed GFRP should be used on 3 sides of specimens. Unfortunately, this study did not provide an explanation for this phenomenon.

FRP debonding

Debonding in FRP strengthened concrete structures takes place in regions of high stress concentrations, which are commonly associated with discontinuities and the presence of cracks. Propagation path of debonding initiates from stress concentrations is affected by the material properties and their interface fracture properties [31]. Majority of the debonding failures reported in the literature occurred in the concrete substrate. However, the mechanical properties of resin play an important role in the debonding failures. Using an inappropriate resin may lead to debonding taking place within the interface elements.

Most of studies about RC beams strengthened by FRP showed that beams failed by debonding of FRP [53, 56-58, 60, 67, 68]. This phenomenon was also reported in ACI 440.2R-08 [15] which mentioned that cover delamination or FRP debonding can occur if the force in the FRP cannot be sustained by the substrate. Hamed and Rabinovitch [69] conducted an analytical study about RC beams strengthened by FRP under impulsive loads and found that the peeling stress developed at the edges of the FRP, this phenomenon unifies with that in the static aspect. Experimental and numerical studies about bonding between FRP and concrete under static tests have shown that high value of shear stress at the interface elements is at or near the end of the FRP [70, 71]. However, Hamed and Rabinovitch [69] concluded that peak shear stresses in the resin were observed at different locations along the beam during the impulsive loads. Also, the peak axial forces in the FRP laminate are developed at different locations along the beams at different times. The location of the critical section in terms of bending moments thus is not always located at midspan.

In addition, the bonding between FRP and concrete in impact tests may be very different from that in static tests. Generally, impact loading is an extremely severe loading condition characterized by a force of great intensity within a short period of time. The behavior of structures under impact loading may consist of two response phases shown in Fig. 3. They are the local response due to the stress wave that occurs at the loading point during a very short period of time after the impact and the overall structural response consisting of the free vibration that lasts relatively longer duration after the impact. It is worth noting that the overall response is predominantly governed by the loading rate effect and the dynamic behavior of the structural member [72]. The two phases may cause double-impact on the bonding which may lead to a reduction of the bond strength.

Stress waves resulted from impact events may cause debonding of FRP strips. When a projectile impacts a beam, it generates stress waves propagating in the beam. The longitudinal wave and the shear wave propagate inside the beam with fast velocity but low energy. Meanwhile, the surface waves (e.g., Rayleigh wave) propagate at a slower velocity but they carry majority of the impact energy (about 67% [73, 74]). The Rayleigh wave travels along the beam surface and causes motion of the surface elements so that they may result in premature debonding of FRP. The debonding of FRP has been observed in almost all the previous experimental studies [53, 56, 58, 67, 68]. Unfortunately, only one study reported the debonding strain of FRP at about 0.4%, which is smaller than that in static tests [56]. The experimental results indicate a reduction of the debonding strain of FRP from concrete could occur. However, this important observation needs to be confirmed with more experimental and numerical studies in the future.

Shear dominance in impact tests

Experimental results have shown that the failure mode of beams may change from the flexural mode under static loads to the shear failure mode under impact loads [59, 62-65]. This interesting phenomenon has been explained in experimental and numerical studies in the literature. When a projectile impacts a beam and accelerates it, the balance condition of the beam is maintained by the participation of the impact force, reaction forces, and inertial forces [59, 75-77]. Saatci and Vecchio [59] experimentally observed that there is no reaction force at the time of the maximum impact force. Therefore, it is reasonable to assume that the impact force is completely resisted by the inertial forces at very early stage of an impact event [59-61, 77, 78]. For simplicity, the distribution of the inertial force along the beams is assumed to be linear. The resulting moment of the beams at the maximum impact force can be estimated in the following two steps: (1) since the sum of the initial force is equal to the maximum impact force, the values of distributed initial force can be computed; (2) considering a half of the beams and taking moment about the midspan section, it has

$$M = \frac{I}{L\left(1-\frac{4a^2}{L^2}\right)}\left(\frac{L^2}{12}-a^2-\frac{4a^3}{3L}\right) \tag{1}$$

where M is the resulting moment, I is the impact force, L is the beam span, and a is the overhang length. As shown a significant shear force, equal to a half of the impact load, and bending moment are generated at midspan of the beam upon impacting, which need to be properly accounted for in the design. More information about estimating the impact force can be found in a previous study [79].

Future Challenges

From the literature, it can be seen that the failure mechanism of the FRP jacket in the impact loading tests has not been thoroughly studied. Even though quite similar design and testing conditions were followed, researchers reported two different failure modes of RC beams strengthened with FRP under impact loading tests. For example, FRP delamination was reported in the study by Tang and Saadatmanesh [56], but it was not observed in the similar tests by the same authors [68]. The failure mechanism of these types of specimens needs to be further investigated so that understanding of the structural performance and accurate prediction of structural capacity can be expected.

In addition, the bonding behavior of FRP and concrete needs be studied in order to develop bond strength models for RC beams strengthened with FRP under impact loading. Strain of FRP during the loading process needs to be measured for understanding this bond mechanism. The debonding strain and the rupture strain of FRP are also needed, which could be the topics for future research.

There is a consensus that the energy absorption capacity of concrete structure significantly increases under the impact loading condition [76, 80]. Strengthening RC structures with FRP also improves the static energy absorption capacity [81] but this definite conclusion cannot be simply made for these structures under impact loading condition due to the lack of studies. There are several popular types of FRP, such as CFRP, GFRP, and AFRP. They have different strength, stiffness, and energy absorption properties and no one FRP material outperforms the other in all aspects [68]. It is thus necessary to investigate the application of different types of FRP used to strengthen RC beams under impact loading conditions.

Impact loads will cause structural vibrations, which will generate negative moments in the beam [56, 68]. These negative moments may not be considered in the design, which may lead to failure of the structures in unexpected manners. Tang and Saadatmanesh [56] thus suggested to bond FRP to both sides of beams; however the rebound response and vibration need to investigate for a better understanding of their effects on structures' behavior. Therefore, it would be suggested that a load cell utilized to measure reaction forces should be able to measure both compression and tension forces, for example the proposed technique by Kishi and Mikami [82] can be utilized. Accordingly, the reverse loads can be qualified in order to provide references for the design.

FRP Strengthened RC Slabs

The dynamic response of RC slabs under impact loads has not received much attention as compared to that under blast loads. Accordingly, studies about impact resistance of RC slab strengthened with FRP under impact loads are extremely limited. Only one study by Bhatti et al. [83] investigated impact resistance of FRP strengthened RC slabs. Bhatti et al. [83] tested nine RC slabs (1,650 x 1,650 x 150 mm) strengthened with two types of FRP including AFRP and CFRP. These slabs were tested under single and multiple blows of drop-weight with a 300 kg steel striker. The study found that the amplitude of displacement of each RC slab increased as the impact velocity increased, and the reaction force increased with the displacement. However, after reaching a maximum value the reaction force decreased as it passed through the loading path. These RC slabs were in the elastic region until the impact velocity reached about 3 m/s. It also showed that the maximum forces for these slabs were reached at the velocity about 3 m/s. Two methods of strengthening were also compared in this study, and it concluded that although using the same amount of FRP, cross-directional bonding to slabs provided higher load carrying capacity than that of the uni-directional bond. The failure modes were found independent of the FRP materials, strengthening methods, and loading types (single or multiple blows). Interestingly, the static capacity ratios tend to be higher than the dynamic capacity ratios, where the static capacity ratio and dynamic capacity ratio are defined as the respective capacity ratio of FRP strengthened slab to that of the non-strengthened slab, respectively.

Meanwhile, more studies investigated the blast resistance of RC slabs strengthened with FRP [84-89]. It was concluded that under blast loading reversed loads might occur so that FRP was recommended to bond on both sides of the slabs. These suggestions are similar to the one suggested for beams under impact loads [56, 68]. Although the study of FRP strengthened RC slab to impact loads is very limited, the response and failure mechanism could be similar to those under blast loads, and to the FRP strengthened beams under impact loads, therefore it is very likely that negative moment will be induced in slabs subjected to impact loads and hence proper strengthening measures need be implemented to account for them. However, this assumption needs to be clarified in impact tests of RC slabs strengthened with FRP.

FRP Strengthened RC Columns

Impact Resistance of confined concrete

Structural behavior of confined concrete has been studied for a few decades. There are two popular types of confined concrete in which confinement can be provided by steel reinforcements (ductile failures observed) and FRP (brittle failure observed). The confined concrete imposed by steel reinforcement has been studied by Scott et al. [90] and Dilger et al. [91]. Test results indicated substantial increases in the compressive strength of the concrete core when strain rate or volumetric ratio of transverse reinforcement increases. The strain at failure decreases as the strain rate increases [90]. Dilger et al. [91] also found that as the strain rate increased, an increase in the compressive strength was observed but the stress-strain curves of confined concrete were not affected.

Recently, FRP is commonly used to strengthen concrete columns. Wrapping FRP material around the perimeter of columns can provide confining pressure on the columns and thus increase the compressive strength of the columns. In the static conditions, strengthening columns with FRP wrap has proven improving the column compressive strength, strain, and ductility [14]. However, the effectiveness of FRP strengthening RC column on its impact resistant capacity has not been well studied yet although a few studies on the composite material properties of FRP-confined concrete under impact loadings have been reported [92-94].

Impact Resistance of FRP-confined concrete

Shan et al. [92] used gas gun testing equipment to study the impact resistance of confined concrete filled tubes, in which concrete was filled in a tube that was externally wrapped with FRP sheets. The maximum strain rate achieved ranged between 530 and 1058 s^{-1}. It was found that damage of these specimens under impact loads was localized to the vicinity of the impact end. The CFRP sheets near the impact end were fractured. Using FRP confinement can significantly improve the compressive strength of the specimens under impact loads.

Uddin et al. [93] utilized an Instron drop-tower testing machine to carry out impact tests on concrete specimens wrapped with thermoplastic composite jackets or CFRP sheets. This study aimed to compare the effects of using two different confinement materials in strengthening concrete cylinders under impact loads. The CFRP sheets were found to be ruptured under impact loads, which led to a brittle failure of CFRP confined concrete specimen. Uddin et al. [93] concluded that energy absorption of the polypropylene was higher than that of the CFRP composites confinement.

Yan and Yali [94] conducted a study on impact behaviors of CFRP confined concrete filled tubes (CCFT) by using a drop-weight testing machine. The CFRP was found ruptured at 2 milliseconds after the impact event. The CCFT specimens had shown improved impact damage resistance. By increasing the number of CFRP layers, the maximum impact force and the duration of the impact event can be increased. This finding proved that CFRP confinement can be used to improve the impact resistance of concrete. Interestingly, an increase in the impact energy did not change significantly the maximum impact loads.

In brief, these studies only qualitatively investigated the impact behaviors of CFRP confined CFT columns. Some conclusions can be made from these study such as using FRP confinement can increase the compressive strength under impact loads and the FRP materials improve the energy absorption of specimens under impact events.

Future Challenges

It can be seen from the literature that studies about impact resistance of FRP-confined concrete column are very limited. There are only a few studies qualitatively described impact behaviors of CCFT columns. The impact resistance of FRP-confined concrete has not been thoroughly studied. Therefore, research studies about this gap of the literature are of importance. Some parameters and effects need be investigated in future studies including: quantify the dynamic increase factor, inertial effects, energy absorption ability of FRP confined concrete composite, effect of FRP stiffness on the composite, and rupture strain of FRP under impact loads.

There are two possible confinement effects that need be studied in FRP-confined concrete. Under axial loads, FRP-confined concrete tends to expand laterally but the confining pressure from the FRP prevents the expansion thus increases the specimen’s capacity. This confinement mechanism is similar to that under static loads. In such cases, the rupture strain of the FRP under impact loads is crucial but it has not been studied yet. In addition, when a projectile impacts a specimen, the concrete tends to expand laterally with an acceleration, which causes the inertial force as a confinement pressure [95]. The axial capacity of the specimen thus increases owing to the lateral inertial confinement effects as shown in Fig. 5. Studies of lateral inertial confinement effect on concrete specimens under impact loads have been reported [94]. No study of the lateral inertial confinement effect of FRP wrapped concrete specimen under impact load has been reported yet. Since FRP wrap will change the lateral expansion acceleration of concrete specimen under impact loads, the lateral inertial confinement effect of FRP confined concrete specimen will be different from that of the non-confined concrete specimen. Therefore, it is important to study the lateral inertial confinement effect of FRP confined concrete specimen in order to obtain the true dynamic material properties of concrete with FRP wrap.

FRP Strengthened Masonry Walls

Introduction

In general, unreinforced masonry (URM) walls have shown poor performance even in moderate earthquakes. Their behavior is usually brittle with little or no ductility and, typically, URM walls suffer various types of damage ranging from invisible cracking to crushing and, eventually, disintegration. This behavior constitutes a major source of hazard during seismic events and creates a major seismic performance problem facing earthquake engineers today.

Structural behavior of URM walls is divided into two types: in-plane response and out-of-plane flexural capacity which is namely as flexural capacity. There are many studies focusing on seismic or static behavior of URM walls [96-102], but only very few studied the URM wall subjected to impact loading [103-105].

Structural Behaviors and Failure Modes of out-of-plane response

Schmidt and Cheng [105] conducted experimental tests on URM walls strengthened with FRP under impact loads. A low-velocity impact load was created by a typical pendulum impact test. Three wall specimens made of masonry with a dimension of 1.2 x 1.2 x 0.2 m were prepared and tested. The first wall acted as a reference specimen while the second and the third walls were respectively strengthened with one and two CFRP layers. The impact loading was applied at the center of the walls using a pendulum system with a total impact mass of 113 kg. This study did not provide a description of failure modes of the tested specimens but concluded that CFRP jacket improved the flexural capacity of the tested specimens. Schmidt and Cheng [105] implemented a parametric study and found that the FRP thickness has a minor effect on the flexural capacity of the wall under impact loading. If the FRP thickness increases from one to two layers, the flexural capacity increases by 2% only, which is much smaller than the corresponding increment of the specimen under static load (26%).

Cheng and McComb [104] cast and tested nine unreinforced concrete masonry walls under low-impact loading. The used pendulum system and the testing protocol were quite similar to those in the study by Schmidt and Cheng [105]. The wall specimens were 1,200 mm wide, 1,200 mm high, and 200 mm thick. Two types of FRP were used in this study, including unidirectional FRP sheets and bidirectional woven FRP. Among different wrapping schemes proposed, some findings can be summarized. By using a similar amount of FRP, the specimen with woven FRP provided higher flexural capacity than that of the specimen with FRP sheets. Strains of FRP of these specimens at failure were 1,333 με and 1,802 με, respectively. These strains are quite small as compared to the design rupture strain recommended by ACI 440.2R-

08 [15]. Other wrapping schemes provided an increase in flexural capacity with an exception of Specimen 5 (no FRP bonded to the contact position). The failure modes of the tested specimens were identical with vertical cracks propagated through the wall thickness and no FRP delamination was observed. Since there was no FRP delamination and low strain in FRP, the use of FRP anchor is meaningless. It is thus recommended not to use anchors in these specimens. In order to compare with the rupture strain of FRP in dynamic tests, the rupture strain of FRP in URM walls strengthened with FRP under non-dynamic loads are summarized in Table 3.

Structural Behaviors and Failure Modes of in-plane response

ElGawady et al. [98] studied the in-plane seismic behavior of masonry infilled walls by testing six full scale walls (3.6 x 3.0 m). GFRP was bonded to two sides of the walls before applying lateral cyclic loads to these walls. Experimental results showed that this strengthening technique provided a higher shear strength of mortar joints and enhanced the stability of the face shell in the out-of-plane direction. This technique was also found to maintain the wall’s structural integrity and prevented collapse and debris fallout as well as increased the energy dissipation of the strengthened walls. The strain of FRP at specimens’ failure was not reported and failure modes were also not presented except Specimen SP5 which showed FRP delamination at failure. The increase in an amount of FRP leads to the improvement of the load-carrying capacity of URM walls and debonding of CFRP was observed [106]. Study of the impact resistance of URM walls in terms of in-plane response has not been reported yet.

Conclusions

This study presents an overview of the impact resistance of FRP strengthened structures including reinforced concrete (RC) beams, RC slabs, RC columns and masonry walls. Although some issues still need to be investigated and clarified, it can be concluded that FRP can be utilized to strengthen and protect structures against impact events. The findings presented in this study are summarized as follows:

1. FRP materials can be used to improve the impact resistance of RC structures including beams, slabs, columns and masonry walls. They lead to an increase in the load carrying capacities, ductility and energy absorption.

2. The tensile strength of FRP materials increases as the strain rate increases while a conclusion on the failure strain and stress-strain relation could not be made.

3. Debonding mechanism of FRP and its rupture strain under impact loads are still unclear.

4. Reverse loads in RC beams and RC slabs may cause negative moments, which lead to unexpected failures. They need to be investigated and taken into account in design.

Finally, FRP material would be recommended for strengthening structures against impact events but further studies are still needed.

References

[1] Bank LC. Composites for construction: structural design with FRP materials. Hoboken, N.J: John Wiley & Sons; 2006.
[2] Oehlers DJ, Seracino R. Design of FRP and steel plated RC structures: retrofitting beams and slabs for strength, stiffness and ductility. Oxford: Elsevier; 2004.
[3] Teng JG, Chen JF, Smith ST, Lam L. FRP-strengthened RC structures. Chichester, West Susses, UK: John Wiley and Sons; 2002.
[4] Hollaway LC, Teng J-G. Strengthening and rehabilitation of civil infrastructures using fibre-reinforced polymer (FRP) composites: Elsevier; 2008.
[5] Hadi MNS, Pham TM, Lei X. New Method of Strengthening Reinforced Concrete Square Columns by Circularizing and Wrapping with Fiber-Reinforced Polymer or Steel Straps. J Compos Constr. 2013;17(2):229-38.

[6] Pham TM, Hadi MNS, Youssef J. Optimized FRP Wrapping Schemes for Circular Concrete Columns. J Compos Constr. 2015;19(6):04015015.

[7] Pham TM, Hadi MNS, Tran TM. Maximum usable strain of FRP-confined concrete. Constr Build Mater. 2015;83:119-27.

[8] Wu Y-F, Jiang C. Effect of load eccentricity on the stress–strain relationship of FRP-confined concrete columns. Compos Struct. 2013;98:228-41.

[9] Nanni A, Bradford NM. FRP jacketed concrete under uniaxial compression. Constr Build Mater. 1995;9(2):115-24.

[10] Nguyen-Minh L, Rovňák M. Shear resistance of GFRP-reinforced concrete beams. Mag Concr Res2011. p. 215-33.

[11] Nguyen-Minh L, Rovňák M, Tran TQ. Punching Shear Capacity of Interior SFRC Slab-Column Connections. J Struct Eng. 2012;138(5):613-24.

[12] Nguyen-Minh L, Rovňák M. Punching Shear Resistance of Interior GFRP Reinforced Slab-Column Connections. J Compos Constr. 2013;17(1):2-13.

[13] Mutalib AA, Hao H. Numerical Analysis of FRP-Composite-Strengthened RC Panels with Anchorages against Blast Loads. Journal of Performance of Constructed Facilities. 2011;25(5):360-72.

[14] Pham TM, Doan LV, Hadi MNS. Strengthening square reinforced concrete columns by circularisation and FRP confinement. Constr Build Mater. 2013;49:490-9.

[15] ACI 440.2R-08. Guide for the Design and Construction of Externally Bonded FRP Systems for Strengthening Concrete Structures. 4402R-08. Farmington Hills, MI: American Concrete Institute; 2008.

[16] TR 55. Design guidance for strengthening concrete structures using fibre composite materials. Camberley: Concrete Society; 2012.

[17] *fib*. Externally bonded FRP reinforcement for RC structures. Bulletin. 2001;14:138.

[18] Buchan PA, Chen JF. Blast resistance of FRP composites and polymer strengthened concrete and masonry structures – A state-of-the-art review. Compos Part B. 2007;38(5–6):509-22.

[19] Banthia NP. Impact resistance of concrete: University of British Columbia; 1987.

[20] Sha Y, Hao H. Nonlinear finite element analysis of barge collision with a single bridge pier. Eng Struct. 2012;41(0):63-76.

[21] Travanca J, Hao H. Energy dissipation in high-energy ship-offshore jacket platform collisions. Marine Structures. 2015;40(0):1-37.

[22] Travanca J, Hao H. Numerical analysis of steel tubular member response to ship bow impacts. Int J Impact Eng. 2014;64(0):101-21.

[23] Sha Y, Hao H. Numerical Simulation of Barge Impact on a Continuous Girder Bridge and Bridge Damage Detection. International Journal of Protective Structures. 2013;4(1):79-96.

[24] El-Tawil S, Severino E, Fonseca P. Vehicle collision with bridge piers. J Bridge Eng. 2005;10(3):345-53.

[25] Cantwell WJ, Morton J. The impact resistance of composite materials — a review. Composites. 1991;22(5):347-62.

[26] Cheresh MC, McMichael S. Instrumented impact test data interpretation. Instrumented Impact Testing of Plastics and Composite Materials, ASTM STP. 1987;936:9-23.

[27] Hao Y, Hao H, Chen G. Experimental investigation of the behaviour of spiral steel fibre reinforced concrete beams subjected to drop-weight impact loads. Mater Struct. 2014:1-18.

[28] Crawford JE, Malvar LJ, Wesevich JW, Valancius J, Reynolds AD. Retrofit of reinforced concrete structures to resist blast effects. ACI Struct J. 1997;94(4).

[29] Crawford JE, Malvar LJ, Morrill KB. Reinforced concrete column retrofit methods for seismic and blast protection. Proc of society of American military engineering symposium on compressive force protection2001.

[30] Davidson JS, Fisher JW, Hammons MI, Porter JR, Dinan RJ. Failure mechanisms of polymer-reinforced concrete masonry walls subjected to blast. J Struct Eng. 2005;131(8):1194-205.

[31] Buyukozturk O, Gunes O, Karaca E. Progress on understanding debonding problems in reinforced concrete and steel members strengthened using FRP composites. Constr Build Mater. 2004;18(1):9-19.

[32] Armenakas A, Sciammarella C. Response of glass-fiber-reinforced epoxy specimens to high rates of tensile loading. Exp Mech. 1973;13(10):433-40.

[33] Eskandari H, Nemes J. Dynamic testing of composite laminates with a tensile split Hopkinson bar. J Compos Mater. 2000;34(4):260-73.

[34] Shokrieh MM, Omidi MJ. Tension behavior of unidirectional glass/epoxy composites under different strain rates. Compos Struct. 2009;88(4):595-601.

[35] Hou Y, Jiang L, Sun B, Gu B. Strain rate effects of tensile behaviors of 3-D orthogonal woven fabric: Experimental and finite element analyses. Test Res J. 2013;83(4):337-54.

[36] Lifshitz JM. Impact Strength of Angle Ply Fiber Reinforced Materials. J Compos Mater. 1976;10(1):92-101.

[37] Daniel I, LaBedz R, Liber T. New method for testing composites at very high strain rates. Exp Mech. 1981;21(2):71-7.

[38] Foroutan R, Nemes J, Ghiasi H, Hubert P. Experimental investigation of high strain-rate behaviour of fabric composites. Compos Struct. 2013;106:264-9.

[39] Benloulo IC, Rodriguez J, Martinez M, Galvez VS. Dynamic tensile testing of aramid and polyethylene fiber composites. Int J Impact Eng. 1997;19(2):135-46.

[40] Rodriguez J, Chocron I, Martinez M, Sanchez-Galvez V. High strain rate properties of aramid and polyethylene woven fabric composites. Compos Part B. 1996;27(2):147-54.

[41] Lifshitz J, Leber H. Response of fiber-reinforced polymers to high strain-rate loading in interlaminar tension and combined tension/shear. Compos Sci Technol. 1998;58(6):987-96.

[42] Hao Y, Hao H, Li Z-X. Numerical analysis of lateral inertial confinement effects on impact test of concrete compressive material properties. International Journal of Protective Structures. 2010;1(1):145-68.

[43] Adams DF, Adams LG. A tensile impact test apparatus for composite materials. Exp Mech. 1989;29(4):466-73.

[44] Harris B, Beaumont PWR, Moncunill de Ferran E. Strength and fracture toughness of carbon fibre polyester composites. J Mater Sci. 1971;6(3):238-51.

[45] Hayes SV, Adams DF. Rate Sensitive Tensile Impact Properties of Fully and Partially Loaded Unidirectional Composites. J Test Eval. 1982;10(2):61-8.

[46] Hancox NL. Izod impact testing of carbon-fibre-reinforced plastics. Composites. 1971;2(1):41-5.

[47] Kimura H, Itabashi M, Kawata K. Mechanical characterization of unidirectional CFRP thin strip and CFRP cables under quasi-static and dynamic tension. Adv Comps Mater. 2001;10(2/3):177-87.

[48] Jadhav A, Woldesenbet E, Pang S-S. High strain rate properties of balanced angle-ply graphite/epoxy composites. Compos Part B. 2003;34(4):339-46.

[49] Gilat A, Goldberg RK, Roberts GD. Experimental study of strain-rate-dependent behavior of carbon/epoxy composite. Compos Sci Technol. 2002;62(10):1469-76.

[50] Barre S, Chotard T, Benzeggagh M. Comparative study of strain rate effects on mechanical properties of glass fibre-reinforced thermoset matrix composite. Compos Par A-Appl S. 1996;27(12):1169-81.

[51] Naik N, Yernamma P, Thoram N, Gadipatri R, Kavala V. High strain rate tensile behavior of woven fabric E-glass/epoxy composite. Polymer Testing. 2010;29(1):14-22.

[52] Sierakowski R. Strain rate effects in composites. Appl Mech Rev. 1997;50(12):741-61.

[53] Soleimani SM, Banthia N, Mindess S. Sprayed GFRP shear-strengthened reinforced concrete Beams under Impact Loading. Advances in Construction Materials: Springer; 2007. p. 279-86.

[54] De Lorenzis L, Teng JG. Near-surface mounted FRP reinforcement: An emerging technique for strengthening structures. Compos Part B. 2007;38(2):119-43.

[55] Cantwell WJ, Smith K. The Static and Dynamic Response of CFRP-Strengthened Concrete Structures. J Mater Sci Lett. 1999;18(4):309-10.

[56] Tang T, Saadatmanesh H. Behavior of Concrete Beams Strengthened with Fiber-Reinforced Polymer Laminates under Impact Loading. J Compos Constr. 2003;7(3):209-18.

[57] Jerome DM, Ross CA. Simulation of the dynamic response of concrete beams externally reinforced with carbon-fiber reinforced plastic. Comput Struct. 1997;64(5–6):1129-53.

[58] Erki M, Meier U. Impact loading of concrete beams externally strengthened with CFRP laminates. J Compos Constr. 1999;3(3):117-24.

[59] Saatci S, Vecchio FJ. Effects of shear mechanisms on impact behavior of reinforced concrete beams. ACI Struct J. 2009;106(1):78-86.

[60] Pham TM, Hao H. Impact Behavior of FRP-Strengthened RC Beams without Stirrups. J Compos Constr. 2016;DOI: 10.1061/(ASCE)CC.1943-5614.0000671:04016011.

[61] Pham TM, Hao H. Behavior of FRP Strengthened RC Beams under Static and Impact Loads. Submitted. 2016.

[62] Magnusson J, Hallgren M, Ansell A. Air-blast-loaded, high-strength concrete beams. Part I: Experimental investigation. Mag Concr Res. 2010;62(2):127-36.

[63] Magnusson J, Ansell A, Hansson H. Air-blast-loaded, high-strength concrete beams. Part II: Numerical non-linear analysis. Mag Concr Res. 2010;62(4):235-42.

[64] Ožbolt J, Sharma A. Numerical simulation of reinforced concrete beams with different shear reinforcements under dynamic impact loads. Int J Impact Eng. 2011;38(12):940-50.

[65] Micallef K, Sagaseta J, Ruiz MF, Muttoni A. Assessing punching shear failure in reinforced concrete flat slabs subjected to localised impact loading. Int J Impact Eng. 2014;71:17-33.

[66] Hughes G, Beeby A. Investigation of the effect of impact loading on concrete beams. Structural Engineer. 1982;60(3):45-52.

[67] White T, Soudki K, Erki M. Response of RC Beams Strengthened with CFRP Laminates and Subjected to a High Rate of Loading. J Compos Constr. 2001;5(3):153-62.

[68] Tang T, Saadatmanesh H. Analytical and experimental studies of fiber-reinforced polymer-strengthened concrete beams under impact loading. ACI Struct J. 2005;102(1):139-49.

[69] Hamed E, Rabinovitch O. Dynamic Behavior of Reinforced Concrete Beams Strengthened with Composite Materials. J Compos Constr. 2005;9(5):429-40.

[70] Smith ST, Teng JG. FRP-strengthened RC beams. I: review of debonding strength models. Eng Struct. 2002;24(4):385-95.

[71] Smith ST, Teng JG. Interfacial stresses in plated beams. Eng Struct. 2001;23(7):857-71.

[72] Fujikake K, Li B, Soeun S. Impact response of reinforced concrete beam and its analytical evaluation. J Struct Eng. 2009;135(8):938-50.

[73] Miller G, Pursey H. On the partition of energy between elastic waves in a semi-infinite solid. Proceedings of the Royal Society of London A: Mathematical, Physical and Engineering Sciences: The Royal Society; 1955. p. 55-69.

[74] Rhazi J, Hassaim M, Ballivy G, Hunaidi O. Effects of concrete non-homogeneity on Rayleigh waves dispersion. Mag Concr Res. 2002;54(3):193-201.

[75] Banthia N, Mindess S, Bentur A. Energy balance in instrumented impact tests on plain concrete beams. Fracture of Concrete and Rock: Springer; 1989. p. 26-36.

[76] Banthia NP, Mindess S, Bentur A. Impact behaviour of concrete beams. Mater Struct. 1987;20(4):293-302.

[77] Cotsovos D, Stathopoulos N, Zeris C. Behavior of RC beams subjected to high rates of concentrated loading. J Struct Eng. 2008;134(12):1839-51.

[78] Cotsovos DM. A simplified approach for assessing the load-carrying capacity of reinforced concrete beams under concentrated load applied at high rates. Int J Impact Eng. 2010;37(8):907-17.

[79] Pham TM, Hao H. Prediction of the Impact Force on RC Beams from a Drop Weight. Adv Struct Eng. 2016;Accepted.

[80] Banthia N, Mindess S, Trottier JF. Impact resistance of steel fiber reinforced concrete. ACI Mater J. 1996;93(5).

[81] Pham TM, Hadi MNS. Strain Estimation of CFRP Confined Concrete Columns Using Energy Approach. J Compos Constr. 2013;17(6):04013001.

[82] Kishi N, Mikami H. Empirical formulas for designing reinforced concrete beams under impact loading. ACI Struct J. 2012;109(4).

[83] Bhatti A, Kishi N, Tan K. Impact resistant behaviour of RC slab strengthened with FRP sheet. Mater Struct. 2011;44(10):1855-64.

[84] Ross CA, Purcell M, Jerome EL. Blast response of concrete beams and slabs externally reinforced with fiber reinforced plastics (FRP). Building to Last: ASCE; 1997. p. 673-7.

[85] Mosalam KM, Mosallam AS. Nonlinear transient analysis of reinforced concrete slabs subjected to blast loading and retrofitted with CFRP composites. Compos Part B. 2001;32(8):623-36.

[86] Lawver D, Daddazio R, Oh GJ, Lee C, Pifko AB, Stanley M. Simulating the response of composite reinforced floor slabs subjected to blast loading. ASME 2003 International Mechanical Engineering Congress and Exposition: American Society of Mechanical Engineers; 2003. p. 15-21.

[87] Wu C, Oehlers DJ, Rebentrost M, Leach J, Whittaker AS. Blast testing of ultra-high performance fibre and FRP-retrofitted concrete slabs. Eng Struct. 2009;31(9):2060-9.

[88] Ghani Razaqpur A, Tolba A, Contestabile E. Blast loading response of reinforced concrete panels reinforced with externally bonded GFRP laminates. Compos Part B. 2007;38(5–6):535-46.

[89] Nam J-W, Kim H-J, Kim S-B, Kim J-HJ, Byun KJ. Analytical study of finite element models for FRP retrofitted concrete structure under blast loads. International Journal of Damage Mechanics. 2008.

[90] Scott B, Park R, Priestley M. Stress-strain behavior of concrete confined by overlapping hoops at low and high strain rates. ACI Journal Proceedings: ACI; 1982.

[91] Dilger W, Koch R, Kowalczyk R. Ductility of plain and confined concrete under different strain rates. ACI Journal Proceedings: ACI; 1984.

[92] Shan JH, Chen R, Zhang WX, Xiao Y, Lu FY. Behavior of Concrete Filled Tubes and Confined Concrete Filled Tubes under High Speed Impact. Adv Struct Eng. 2007;10(2):209-18.

[93] Uddin N, Purdue JD, Vaidya U. Feasibility of thermoplastic composite jackets for bridge impact protection. Journal of Aerospace Engineering. 2008;21(4):259-65.

[94] Yan X, Yali S. Impact Behaviors of CFT and CFRP Confined CFT Stub Columns. J Compos Constr. 2012;16(6):662-70.

[95] Hao Y, Hao H, Jiang GP, Zhou Y. Experimental confirmation of some factors influencing dynamic concrete compressive strengths in high-speed impact tests. Cement and Concrete Res. 2013;52(0):63-70.

[96] El-Dakhakhni W, Hamid A, Elgaaly M. Seismic Retrofit of Concrete-Masonry-Infilled Steel Frames with Glass Fiber-Reinforced Polymer Laminates. J Struct Eng. 2004;130(9):1343-52.

[97] Almusallam T, Al-Salloum Y. Behavior of FRP Strengthened Infill Walls under In-Plane Seismic Loading. J Compos Constr. 2007;11(3):308-18.

[98] ElGawady M, Lestuzzi P, Badoux M. In-Plane Seismic Response of URM Walls Upgraded with FRP. J Compos Constr. 2005;9(6):524-35.

[99] Ehsani M, Saadatmanesh H, Velazquez-Dimas J. Behavior of retrofitted URM walls under simulated earthquake loading. J Compos Constr. 1999;3(3):134-42.

[100] Ozden S, Akguzel U, Ozturan T. Seismic Strengthening of Infilled Reinforced Concrete Frames with Composite Materials. ACI Struct J. 2011;108(4).

[101] Al-Chaar GK, Hasan HA. Dynamic response and seismic testing of CMU walls rehabilitated with composite material applied to only one side. Proceedings of the ICE-Structures and Buildings. 2002;152(2):135-46.

[102] Shrive NG. The use of fibre reinforced polymers to improve seismic resistance of masonry. Constr Build Mater. 2006;20(4):269-77.

[103] Gilbert M, Hobbs B, Molyneaux TCK. The performance of unreinforced masonry walls subjected to low-velocity impacts: experiments. Int J Impact Eng. 2002;27(3):231-51.

[104] Cheng L, McComb AM. Unreinforced concrete masonry walls strengthened with CFRP sheets and strips under pendulum impact. J Compos Constr. 2010;14(6):775-83.

[105] Schmidt ME, Cheng L. Impact response of externally strengthened unreinforced masonry walls using CFRP. J Compos Constr. 2009;13(4):252-61.

[106] Triantafillou TC. Strengthening of masonry structures using epoxy-bonded FRP laminates. J Compos Constr. 1998;2(2):96-104.

[107] Jerome DM. Dynamic response of concrete beams externally reinforced with carbon fiber-reinforced plastic [Ph.D.]. Ann Arbor: University of Florida; 1996.

[108] Jerome D, Ross C. Simulation of the dynamic response of concrete beams externally reinforced with carbon-fiber reinforced plastic. Computers & structures. 1997;64(5):1129-53.

[109] Hamoush SA, McGinley MW, Mlakar P, Scott D, Murray K. Out-of-plane strengthening of masonry walls with reinforced composites. J Compos Constr. 2001;5(3):139-45.

[110] Tan KH, Patoary M. Strengthening of masonry walls against out-of-plane loads using fiber-reinforced polymer reinforcement. J Compos Constr. 2004;8(1):79-87.

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Table 1. Summary studies on dynamic properties of FRP

Study	Test method	*Observations*			
		Tensile strength	*Failure strain*	Stress-strain curves	Modulus[#]
Armenakas and Sciammarella [32]	E	-	higher[*]	linear	higher[*]
Daniel et al. [37]	-	no change	no change	linear	higher
Lifshitz [36]	D	higher	no change	linear	no change
Hayes and Adams [45]	P	lower	-	-	higher
Barre et al. [50]	D	higher	-	linear	higher
Rodriguez et al. [40]	T	higher	lower	nonlinear	-
Benloulo et al. [39]	T	higher	lower	nonlinear	-
Lifshitz and Leber [41]	T	higher	-	linear	higher
Eskandari and Nemes [33]	T	higher	higher	linear	-
Gilat et al. [49]	T	higher	-	nonlinear	higher
Shokrieh and Omidi [34]	S	higher	higher	linear	higher
Naik et al. [51]	T	higher	-	-	-
Foroutan et al. [38]	T	higher	lower	nonlinear	-
Hou et al. [35]	T	higher	higher	nonlinear	-

E = explosively driven hammers

D = drop weight apparatus

P = pendulum apparatus

T = tensile split Hopkinson bar

S = servo-hydraulic testing apparatus

[-] no or unclear particular conclusion

[*] as compared to the corresponding values of the fiber

[#] in case of nonlinear relationship, the modulus is the initial modulus when the materials behave linearly

Table 2. Summary studies on FRP strengthened RC beams

Study	Section (mm)	Span (m)	f_c' (MPa)	Type of FRP	Testing method				
					Apparatus	Mass (kg)	Height (m)	Rate (10^{-3}/s)	Velocity* (m/s)
Jerome [107]	76x76	0.69	46.4	CFRP	D	43.7	0.61	18	2.6
Jerome and Ross [108]	76x76	-	46.4	CFRP	D	43.7	0.61	18	2.6
Erki and Meier [58]	400x300	7.85	65.6	CFRP	Lift - drop	-	0.5-2.0	0.8	-
White et al. [67]	150x300	2.80	45.6	CFRP	-	-	-	6.93	0.04
Tang and Saadatmanesh [56]	203x95	1.83	27.6	CFRP/ KFRP	D	22.6	1.5-3.7	1.4	-
Tang and Saadatmanesh [68]	203x95	1.98-2.9	-	CFRP/ KFRP	D	22.6	0.3-1.7	1.4	-
Soleimani et al. [53]	150x150	0.80	-	Sprayed GFRP	D	591	0.8	-	3.96

D = drop weight apparatus

Lift – drop = beams were lifted to a certain height and then dropped

$^-$ no data reported

* highest velocity in the tests

Table 3. FRP strain in URM walls strengthened with FRP

Study	Type of FRP	FRP strain (%)	Failure modes	Loading condition
Out-of-plane behavior				
Ehsani et al. [99]	GFRP	1.2	FD	A
Hamoush et al. [109]	GFRP/KFRP*	~0.2	FD	A
Tan and Patoary [110]	GFRP/CFRP	-	FD/FR	C
In-plane behavior				
Triantafillou [106]	CFRP		FD	F
ElGawady et al. [98]	GFRP fabric	1.2/3.0	FD/AF/FR	S
	GFRP grids	2.5/4.0	FD/AF/FR	S

A = airbag confined in a plywood box was used to apply the out-of-plane pressure

C = Concentrated load

S = Shake table

F = four-point pending tests

FD = fiber delamination

AF = anchor fail

FR = fiber rupture

* KFRP is Kevlar FRP

ADDRESSING REVIEWERS' COMMENTS

Ms. Ref. No.: STRUCTURES-D-15-00158

Title: Review of Concrete Structures Strengthened with FRP against Impact Loading

The authors would like to thank the editors/reviewers for their time and effort spent into reviewing the manuscript. Their comments and suggestions have contributed to the improvement of the revised manuscript. All recommendations and comments have been carefully taken into consideration.

Reviewers' comments:

Reviewer #1: *This reviewer recommends an acceptance of the paper for publication. The written English needs improvements. Just scanning the first few lines of the manuscript shows the following statements that should be revised: "some issues still need be investigated", "Resent global terrorism...", "have been increasingly attracted the...", "the understanding... been... studied...". Furthermore, more in-depth review by including analytical studies would improve the paper, e.g. using existing analytical models or numerical simulations to study statically loaded cases and then comparing it with those cases reviewed in the paper.*

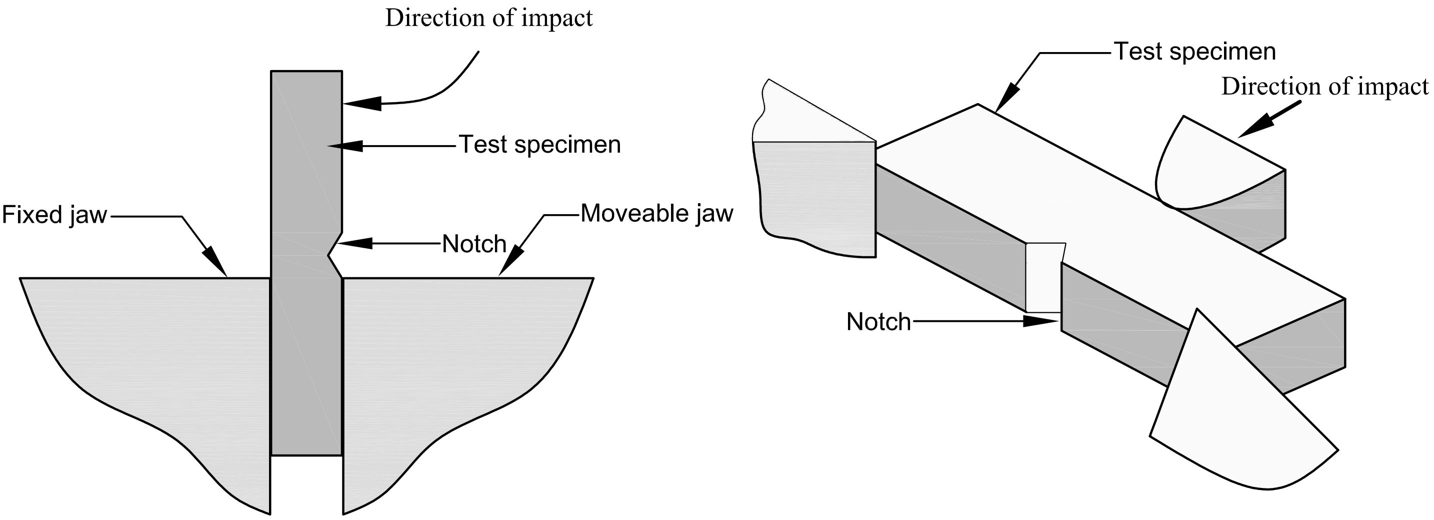
The written English of the manuscript has been checked throughout and revised accordingly. Please refer to Lines 19, 24-26, 33-34. More studies were added to compare the behavior of structures under static loads and impact loads. Please refer to Lines 345-374. Numerical studies have been reviewed and discussed in the manuscript. Please refer to Lines 395-404.

Reviewer #2: *The authors have provided a comprehensive review on the topic of impact resistance of structures (both masonry and reinforced concrete) strengthened with FRP. However, the review wonders why they have lumped the review on masonry and reinforced concrete in one article. The reviewer would suggest that title of the article be amended to Review of Concrete Structures Strengthened with FRP against Impact Loading.*

The title of the manuscript has been revised accordingly to the comment. Please refer to Lines 1-2.

Figure

Fig. 1.



Izod pendulum

Charpy pendulum

Fig. 2.

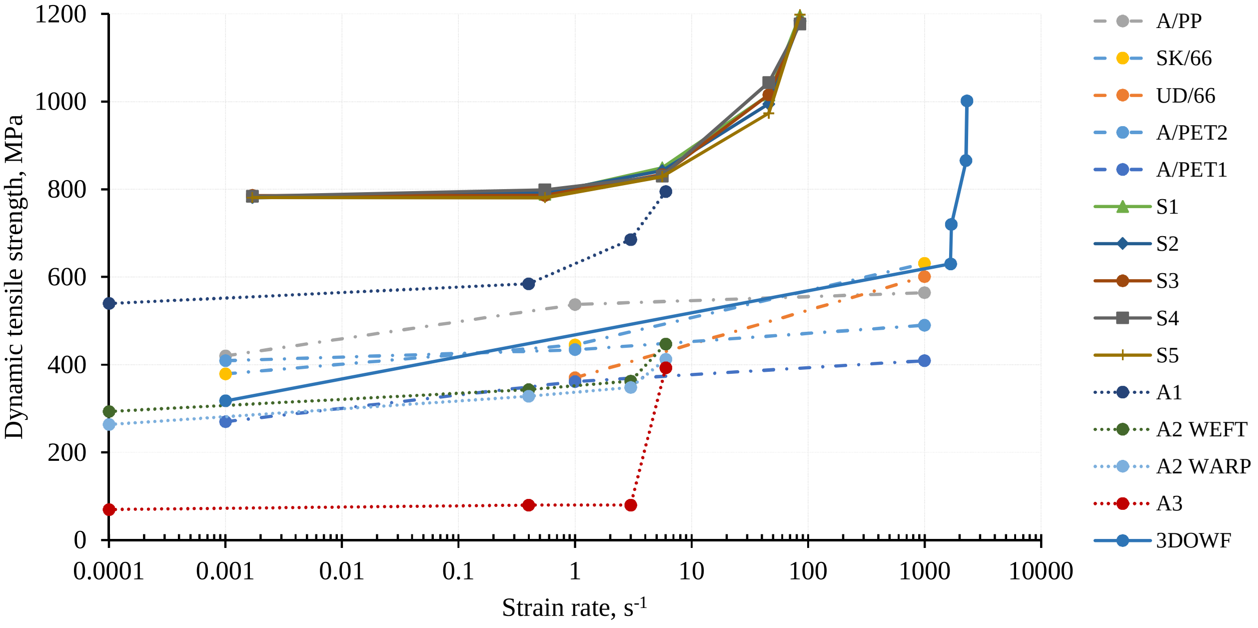

Dynamic tensile strength, MPa
1200
1000
800
600
400
200
0
0.0001
0.001
0.01
0.1
1
10
100
1000
10000
Strain rate, s^{-1}
A/PP
SK/66
UD/66
A/PET2
A/PET1
S1
S2
S3
S4
S5
A1
A2 WEFT
A2 WARP
A3
3DOWF

Fig. 3.

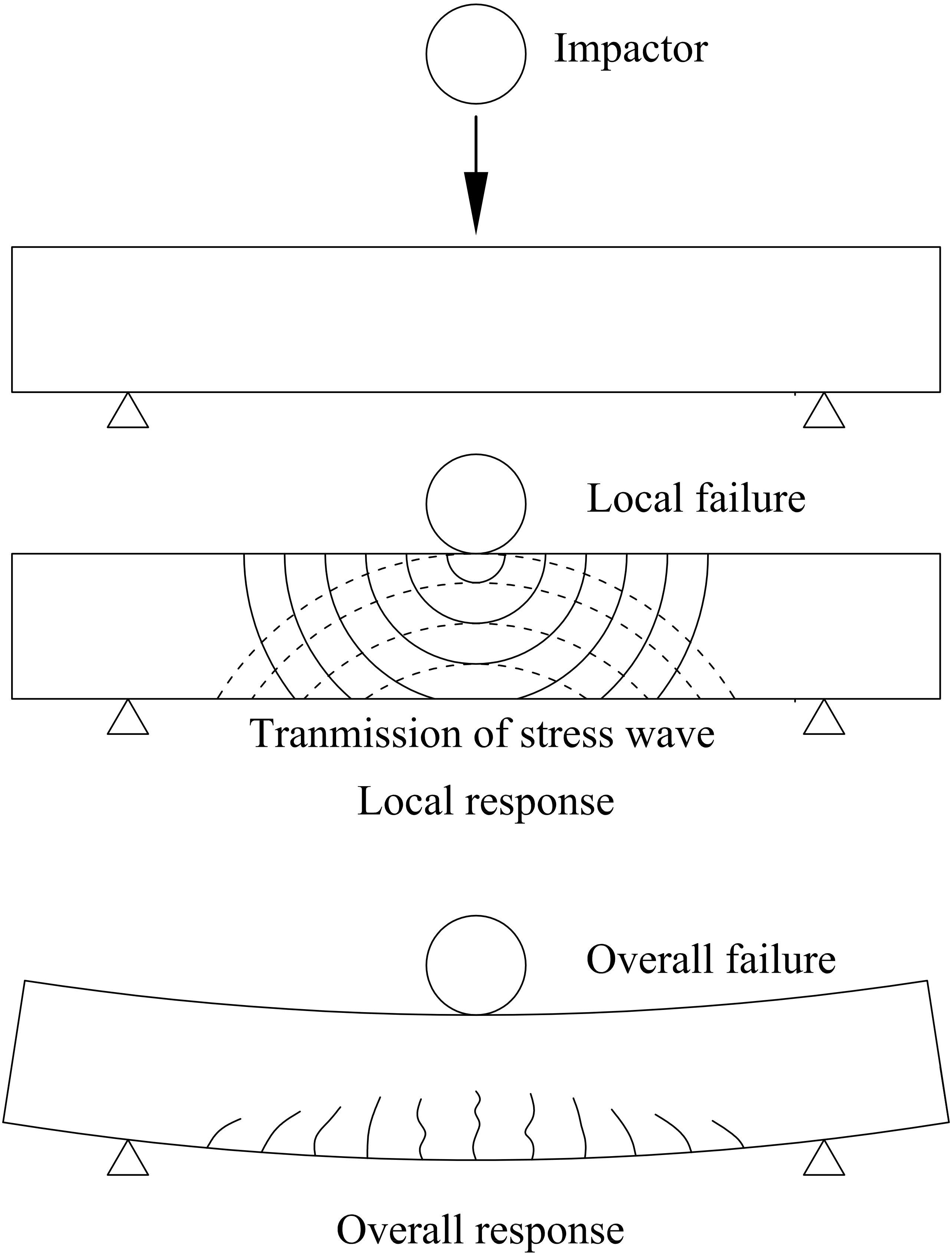
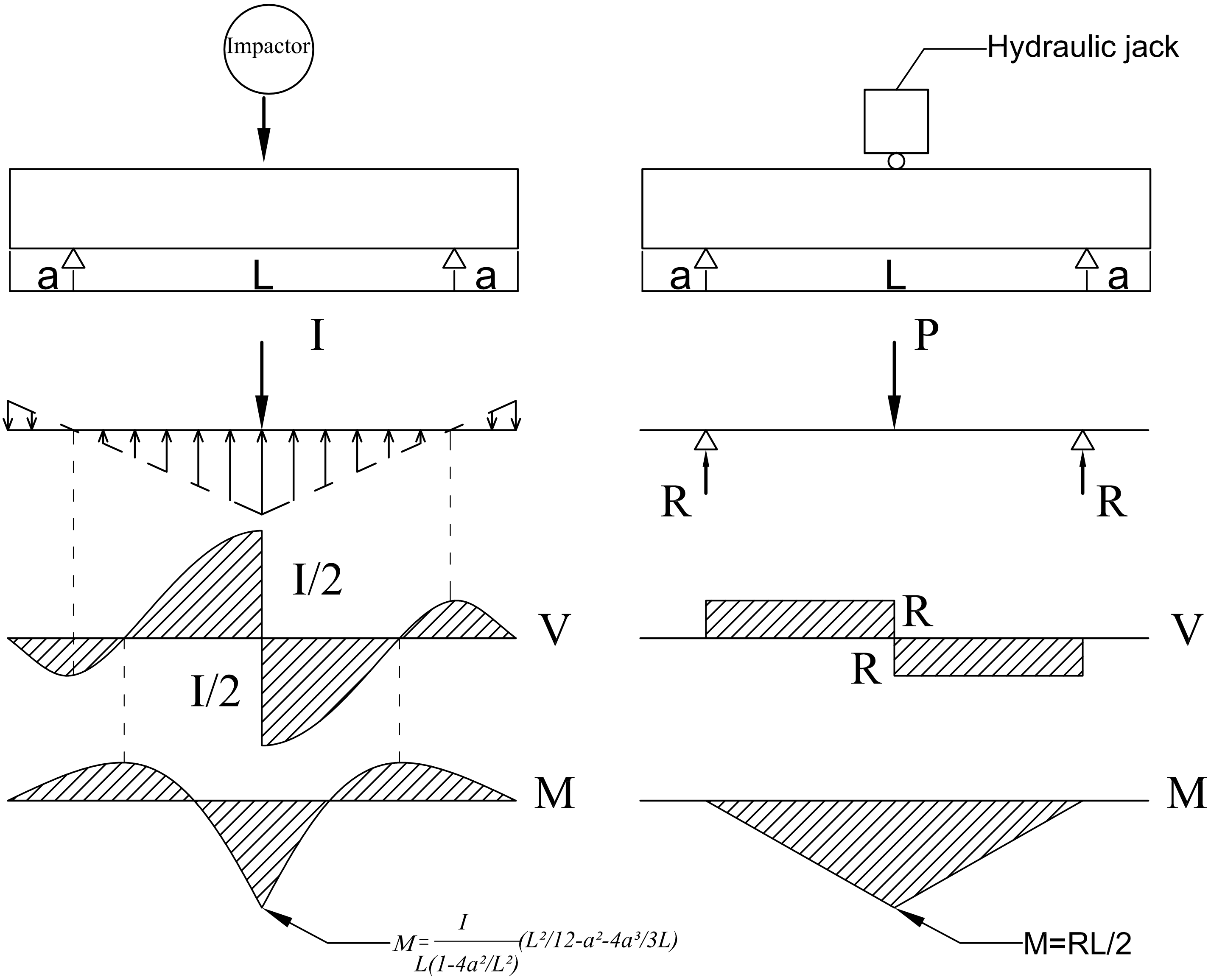

Impactor
Local failure
Tranmission of stress wave
Local response
Overall failure
Overall response

Fig. 4



Dynamic

Static

Fig. 5