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Review of laboratory methods for drop weight testing of concrete beam members

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ABSTRACT

The adopted in-lab methodology for conducting impact tests on concrete beam members makes use of a drop weight apparatus. Drop weight tests are conducted by dropping a weight of significant mass, usually in the form of a flat or conical shaped hammer, onto the specimen. These tests rely solely on the use of gravity to accelerate the hammer to impact. Loading is controlled by the mass of the impact hammer and the height at which the hammer is dropped. Many drop weight tests have been conducted in regard to concrete beams loaded in this manner. Early studies have focused on establishing a general behavior of concrete beams under extreme impact with recent investigations aimed at providing quantifiable design guidelines. This review was conducted in order to identify the trends and methods used for drop weight tested concrete beams. Detail is given to the testing configuration, beam instrumentation, and the collected data. Evaluated literature encompasses research as published from the mid 1980s to present day.

1. INTRODUCTION

While the understanding of the static behavior of various structural elements has been well established, the understanding of the dynamic characteristics under impact is still largely an ongoing process. This is due to the complexities associated with such tests, with difficulties attributed to member instrumentation and data collection as member failure is relatively instantaneous. Additionally, in regard to the extreme loading conditions such as those associated with large explosions or the collisions of automobiles into transportation structures, the use of full scale structural testing is not

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always the best choice in regard to costs, fabrication and overall feasibility. Therefore, impact tests have been commonly restricted to the testing of singular elements.

Tests of concrete members have commonly involved the testing of beam members under impact. The adopted in-lab methodology for conducting impact tests makes use of a drop weight apparatus. Appropriately named, these tests are conducted by dropping a weight of significant mass onto the specimen. Basic methodology of these tests relies solely on the use of gravity for acceleration. Loading is controlled by the mass of the weight and the height at which the weight is dropped. These tests represent one of the simplest laboratory methods used to understand the behavior concrete elements under impact. A general overview of these tests is given in the following sections.

2. APPARATUS

Configuration of the drop weight apparatus consists of a rigid steel frame and twin rail system. The weight used to impact the specimen, referred to as the hammer, is hoisted along the railing which is used to guide the impacting mass towards the specimen. Once the hammer is released, the kinetic energy impacting the specimen is solely based on the use of gravity. It should be noted that these tests represent a hard impact scenario in which all deformation is done to the beam specimen, which is impacted in a three-point bending configuration. Fig. 1 provides a general representation of a drop weight apparatus.

In order to prevent multiple impacts of the hammer onto the specimen, a hydraulic brake system is usually employed that is able to catch the specimen after the initial impact. Careful detailing must also be done at the support conditions as early authors such as Bentur et al. (1986) noted the importance of intimate contact between the bottom face of the concrete specimen and the reaction support, as the interface of the beam can separate from the reaction support during impact. To reduce this effect and obtain accurate load response, many authors have implemented the use of steel yokes at the supports (Shafei et al., 2015). This was done in combination with a steel plate at the top surface of the beam to stabilize the beam from any bounce back at the time of impact. This detail can be seen in Fig. 2 (Left). Goldston et al. (2016) were also able to obtain accurate results through the use of straps to prevent the uplift. Additionally, Chen and May (2009) fabricated a pin ended support composed of welded plates, shown in Fig. 2 (Right).

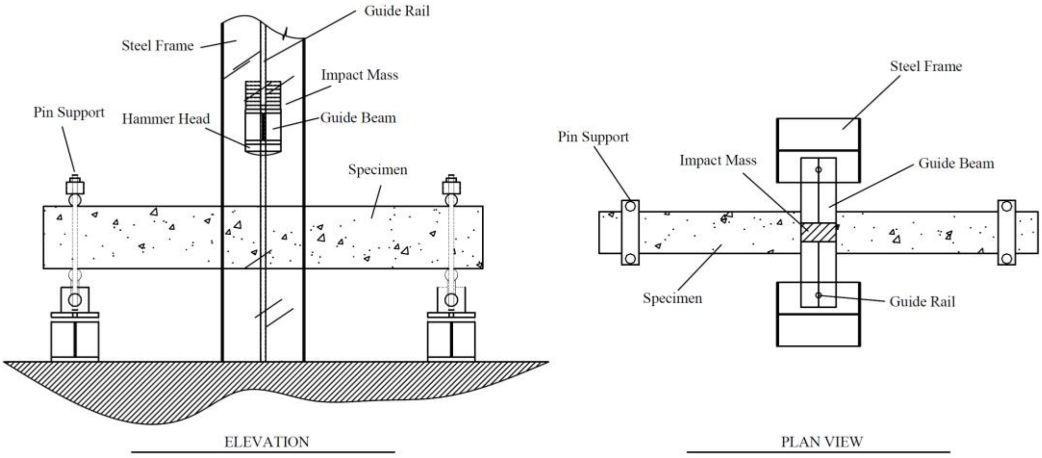

Fig. 1 General drop weight apparatus

Fig. 2 Steel yoke type support as used by Shafei et al. (2015) [left]; Fabricated box plate support as used by Chen and May (2009) [right]

3. OVERVIEW OF TESTED SPECIMENS

Early investigations, as those performed by Naaman and Gopalaratnam (1983) were done on 12.5 x 75 mm rectangular specimens with a length of 300 mm; however, common sizes of tested specimens have been much larger in the range of 100 mm to 250 mm in width and depth and tested with clear spans up to 2 m. Studies have focused on comparing strength characteristics and failure modes of plain concrete (PC), conventionally reinforced concrete (RC), and fiber reinforced concrete (FRC) specimens. In regard to FRC beams, specimens have been tested with and without the presence of steel rebars. Additionally, studies have also been performed on retrofitted beams with external fiber reinforcement in the form of bonded fiber reinforced textiles and sprayed directly on to the surface (Shafei, 2015; Goldston, 2016). One notable study of fiber reinforced specimens under impact was also done by Banthia et al. (1998) in which the authors studied the performance of PC and FRC specimens without traditional rebars under extreme subnormal temperatures.

During testing, the member can be loaded in three ways. Specimens can be failed with a single drop of the impacting hammer as done by Mindess et al. (1986) and other authors (Bentur, 1986; Kishi et al., 2001; Kishi et al., 2002; Sukontasukkul and Mindess, 2003; Wu et al., 2016) or impacted repeatedly under the same mass and drop height conditions until failure of the specimen is reached (Barr et al., 1988; Shafei et al, 2015). While not as common as single or repeatedly impacts, another method of testing includes the method of incrementally impacting the beam. This type of testing involves repeatedly impacting the same specimen with increasing impact velocity or drop height after each successive drop until failure. This type of testing has been performed by authors such as Kishi et al. (2001) and Ishikawa et al. (2002). Additionally, testing has also been done on statically pre-damaged beams by Mindess et al. (1986). Common impacting velocities have been in the range of 1 to 6 m/s with hammers weighing in between 100 and 300 kg.

4. GENERAL CHARACTERISTICS

4.1 Inertial Loading

It has been well established that the impacting energy is not completely absorbed by the beam to resist shear and bending. Instead some of this energy is resisted by the beam in the form of inertia to maintain balance. Bentur et al. (1986) observed that this inertial energy may account for more than 2/3 of the total impact. The total impacting load is equated as the summation of the inertia load and the load contributing to failure of the specimen. See equation below, in which $P_t(t)$, $P_b(t)$, and $P_i(t)$ refer to the total load as measured at the point of impact and the loading attributed to bending and inertia, respectively.

$$P_t(t) = P_b(t) + P_i(t) \qquad (1)$$

The nature of these dynamic characteristics have made it difficult to accurately assess the loading contributing to deformation and failure of the beam specimens. In order to quantify the deforming load (P_b), Bentur et al. (1986) set out to evaluate the inertia loading (P_i). Using methods of virtual work, the authors were then able to quantify the inertial load in terms of the clear span, length of overhang, beam density, and acceleration. Their development of this method included the following test, in which accelerometers were attached directly to the beam surface along the member span. Both PC and RC beams were impacted and the distribution of accelerations were observed. While under impact, they noted that PC beams showed a linear distribution of acceleration while a sinusoidal distribution was largely observed for RC beams (Fig. 3). However, in their verification, it was shown that RC beams were insensitive in regard to the assumption of a linear or sinusoidal distribution, concluding that a linear distribution could also be used for assessing the inertial loading of RC members. See equations below.

$$P_i(t) = \rho A\ddot{u}_0(t)\left[\frac{l}{3} + \frac{8}{3}\frac{h^3}{l^2}\right] \quad (2)$$

$$P_i(t) = \rho A\ddot{u}_0(t)\left[\frac{l}{2} + \frac{2\pi^2}{3}\frac{h^3}{l^2}\right] \quad (3)$$

where the terms ρ, A, l, h and $\ddot{u}_0$ refer to density, cross sectional area, span length, length of overhang, and acceleration, respectively.

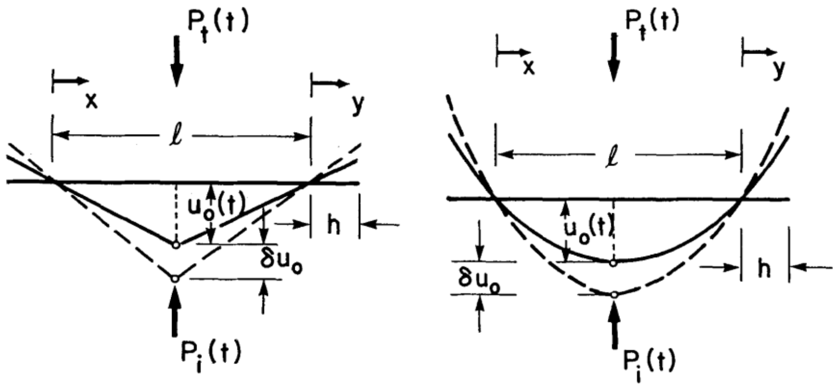

Fig. 1 Acceleration distribution of PC members [left];
Acceleration distribution of RC members [right] (Bentur et al., 1986)

There have been other methods at determining the true bending loads. In tests of Soleimani et al. (2007), load cells were placed at both supports and the bending load was calculated as the summation of the peak reaction loads as measured at the left and right supports. In their tests the inertial load was observed to be 86% to 98% of the total load. A similar approach was done by Zhang et al. (2010). They observed the inertia load equal to be 82.5% of the impacting load. See equation below, where R_a and R_b refer to the maximum reaction obtained at the left and right supports, respectively.

$$P_b(t) = R_a(t) + R_b(t) \quad (4)$$

4.2 Impulse

The transfer energy between the hammer and the beam can be understood by investigation of the impulse behavior. For PC and FRC members without conventional rebars, behavior of the impacting load in relation to time is denoted by a single peak sine wave followed by rapid dissipation. This was noted by Mindess and Bentur (1985). The peak load was shown occurring at about 1 ms after initial impact and rapidly decreasing to 0 N at a time less than 10 ms from the initial impact. With the addition of fibers, the time required for dissipation of the impacting load increased to roughly 25 ms, more than a factor of 2. This denotes a better transfer of energy from the hammer to the specimen resulting in an increase in contact time of the hammer with the specimen. While the behavior of PC and FRC beams without rebars can be defined by a single sinusoid type wave, the behavior of RC specimens are defined by an initial peak wave, similar to that as observed in PC specimens, followed by multiple oscillating waves until the load is completely zeroed out. Loading of RC specimens is much longer than that of PC specimens. Mindess and Bentur (1985) observed a dissipation time of 70 ms compared to the 10 ms time as shown for PC specimens. This behavior was also observed by Bentur et al. (1986). Generalized behavior of impulse is given in the figure below.

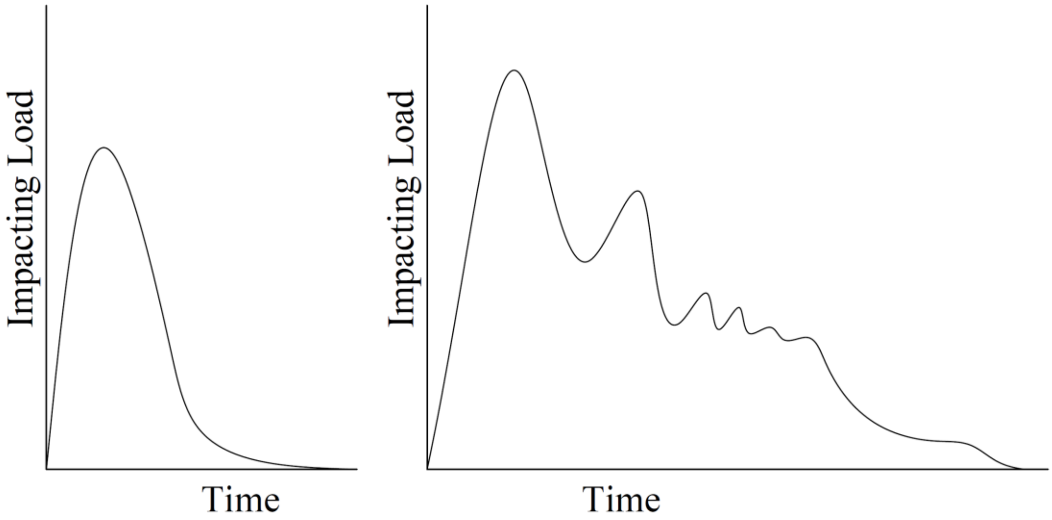

Fig 2 General impulse behavior of plain members [left];
Rebar-reinforced members [right]

4.3 Shear and Flexure Deficient Members

The impact behaviors of shear and flexure deficient beams are significantly different. In-depth studies done by Kishi et al. (2001 & 2002) highlight these variances. From these investigations, the authors were able to quantify the energy absorption of both shear and flexure deficient members in terms of the impacting reaction force and the accompanying residual deflection. For flexure deficient beams, the authors were able to simplify this relationship as a parallelogram, while shear deficient beams were observed to follow a triangular distribution.

Additionally for flexure deficient members, comparisons of the maximum observed reaction force with that of the static capacity showed the reaction force surpassed the design capacity by a factor of 2. As noted in the section above, not all impact energy is absorbed for fracture of the beam, the authors observed the ratio of absorbed energy to kinetic energy to be 0.7. In regard to shear members, these values were observed to be in the range of 1.5 to 2.5 and 0.60 for the ratio of reaction force to static capacity and the ratio of absorbed energy to kinetic energy, respectively.

5. CONCLUSION

The testing of beam members through the use of a drop weight machine provides valuable insight to the behavior of concrete beams under impact. However, due to the uncertain nature of concrete dynamic behavior, there still exists much information to be obtained. While early tests were primitive in regard to the data collection techniques and instrumentation used. The data gained from recent tests have been able to provide much detail on the failure mechanism of various concrete beam configurations. As noted above, the study of fiber reinforced concrete matrices has been extensively conducted on plain and traditionally reinforced beam members with both normal and high strength concrete. However, there still exists much to be learned through the use of drop weight testing. Due to the unforeseen dynamic loading conditions, the understanding of structural failure under impact has become more relevant than in the past, and it is important to continue research in the area of concrete elements under impact.

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