

Impact Testing of Concrete

The Measurement Device

Petr Máca, Radoslav Sovják, Petr Konvalinka

Abstract—Testing of ultra high performance fiber reinforced concrete under impact loading is described in this paper. In addition a design process of a novel impact measurement device is presented in this work. There are several ways how to test impact resistance of concrete and various groups throughout the world developed different testing devices. Most of such devices are based on a principle of a falling weight on the concrete specimen. This work however presents an impact machine that is based on a pendulum principle. Such test configuration has several advantages, such as elimination of double hits, easy access to the sample and high degree of device modulability. In addition, the placement of sensors and high speed camera is relatively easy. In this experimental work concrete beams were tested in the testing device, but the test setup can be rearranged to test slabs or joints. The calibration process of the machine is shown in this paper as well as the results from impact resistance measurement of high performance fiber reinforced concrete.

Keywords—impact, high performance concrete, horizontal loading

I. Introduction

Response of concrete subjected to impact loading is of the main interest of several military and civil applications. In recent years there is an increase interest in testing concrete elements by using proper dynamic analysis. When it comes to impact testing of concrete, the main issues encountered by many researchers are insufficiently fast data acquisition systems, vibrations in the loading frame and resonant frequency of the sensors. These issues then lead to apparent energy losses and large variance of the results between the laboratories. The large variance of the results is also connected with different techniques used for studying mechanical properties of concrete and concrete structures under dynamic loading. For instance, several authors used modified Charpy impact test [1] to study impact behavior of concrete in bending. The modified Charpy test is limited by size of the sample and weight of the impact pendulum. Another way how to assess impact-bending properties of concrete are methods based on a principle of weight falling down on the sample from specified height, so called drop tower tests [2-4]. The disadvantage of these methods is the fact that a so called double hit caused by rebound of the impactor can occur in case when the specimen is not fully broken by the first blow of the impactor.

Concrete in compression or direct tension subjected to high strain rates is usually tested by utilization of split Hopkinson pressure bar (SHPB). The compression loading can be uniaxial [5-7] or biaxial. The biaxial method is still in development but promises good results [8, 9]. The basic principle of the method is that the specimen is placed between two long aluminum bars and an impulse is developed by a pressure gun into one of the bars. Impulse transmission is monitored by strain gauges and the difference between the magnitude of the pressure wave before and after the destruction of the specimen is acquired. The main disadvantage of this method is the fact, that the specimens are relatively small, usually cylinders with a diameter of 50 mm. This paper describes a new machine that has been constructed specifically for dynamic testing of concrete. At the moment the machine is in the bending loading configuration but it is relatively easy to transform it into the slab testing setup. The instrumentation and construction process of the machine is described in the paper.

II. Principle of the impact machine

The required horizontal loading setup and space capacity of the laboratories of the Czech Technical University governed the design of the impact machine. The target impact kinetic energy was set to 2000 J in the initial design, resulting in machine capable of dropping a 50 kg impactor from a height of 4 m. In general, for impact test machines, there are several possible setups that can be divided into two groups, according to the direction of impact i.e. horizontal and vertical impact. The setup presented in this paper utilizes horizontal impact direction with stationary specimen where the impactor is following a circular trajectory using guide elements. The schematic diagram of the pendulum machine is shown in Fig. 1. The energy of the impact can be varied by placing the hoist of the impactor in different positions along the left column. The impactor is shown in three possible positions-heights in Fig. 1. The specimen is placed near the bottom return point of the impactor trajectory. This setup has several advantages and disadvantages, compared to the more conventional vertical impact. The advantage is that it is easier to avoid double impact just by geometric arrangement. The specimen is placed little further on the impactor trajectory, and due to the circular shape, little above, i.e. the point of impact is not the least potential point on the trajectory. Once the impactor hits the specimen, it rebounds and tends to balance in the bottom-return point of trajectory, not hitting the specimen again.

Petr Máca, Radoslav Sovják, Petr Konvalinka
Czech Technical University in Prague, Faculty of Civil Engineering
Czech Republic

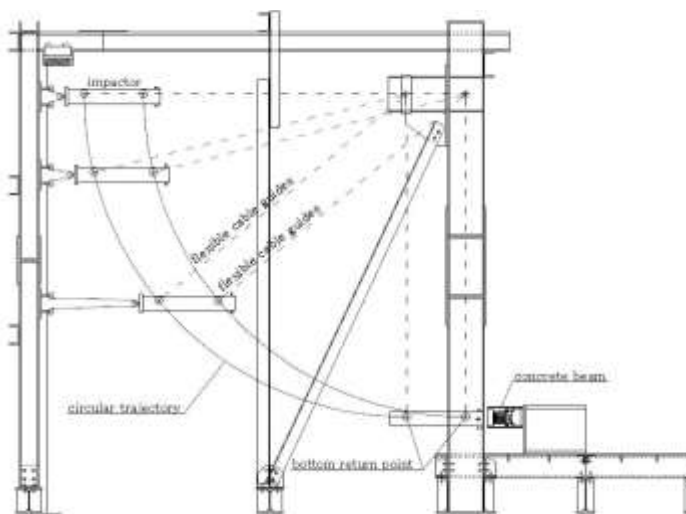


Figure 1. Schematic design of an impact pendulum machine. The impactor is shown in several possible launching positions.

The machine itself consists of several structural groups as shown in Fig. 1. These groups are the impactor support group, impactor guide group (Fig. 2) and specimen support group that is shown in detail in Fig. 3. These groups are highly modular and can be easily replaced. The impactor itself can be replaced as well. There were already five designs tested so far with different weights and cross-sections from welded lightweight I-beams to solid rectangular steel bars. The impactor itself is instrumented with a set of accelerometers as shown in Fig. 2. It is possible to place the accelerometers to various positions along the impactor. The most interesting placement is near the top of the impactor where four positions are available – top, bottom, right and left from the top. It is also possible to place an accelerometer to the rear face of the impactor to measure the vibration of the impactor itself.

As long as the machine was intended as a prototype from the beginning, all parts are designed completely interchangeable and modular. It is possible to adjust the position of the axis of the impactor circular trajectory in 500 mm increments, from 1.5 to 3.0 m above the specimen position. Initially, the design was supposed to utilize drop height of double the axis height (with top point of trajectory above the axis level), using rigid guides. The rigid guides were designed as lightweight as possible, not to interfere with the impact mass, using duralumin profiles. During the testing of the machine, it was found out that the resonant frequency of the rigid guides was very near to the measured values during impact on concrete. For this reason it was impossible to filter this resonant frequency from the accelerations measured at the impactor top and the design had to be changed.

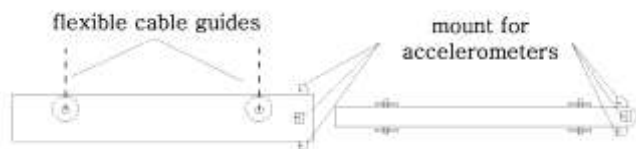


Figure 2. Location of accelerometers along the impactor.

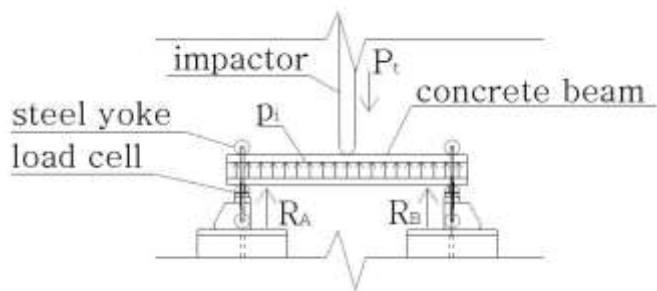


Figure 3. Specimen support group, top view.

To eliminate the resonant frequencies, the design change lead to replacing the rigid guide with flexible cable guides. Such solution smoothed out the acceleration readings, but resulted in the impossibility of dropping the impactor from heights above the circular trajectory axis.

The specimen itself is connected with steel yokes to the supports that are instrumented with load cells. The placement of the specimen is shown in detail in Fig. 3, the view is from above. The steel yokes allow the specimen to rotate freely along the support as is shown in Fig. 4. This setup has an additional advantage as it restrains the uplift of the specimen. At the moment the machine is prepared for measuring beams with a cross-section of 100×100 mm. The span of the beam can be from 300 mm to 1000 mm.

A. Measurement

Proper dynamic analysis that takes into account inertial forces needs to be performed to adequately measure impact behaviour of larger concrete elements where high accelerations exist. There are several methods how to diminish the influence of the inertial forces. Sometimes an attenuator, usually made of plywood, is introduced in the contact zone between the loading impactor and the specimen [10, 11]. To overcome the inertia, it is also possible to carry out a numerical analysis but this is fairly complex task. An experimental way how to deal with inertia was suggested in their work by Bentur et al. [12]. They proposed direct measurement of acceleration along the concrete specimen. In case a linear distribution of acceleration along the specimen is assumed, it is possible to calculate the acceleration at the mid-span of the specimen that is denoted $\ddot{u}_o(t)$. If the mass density ρ and cross-sectional area A remain constant throughout the length of the beam, it is possible to calculate the inertial load as

$$P_i(t) = \rho A \ddot{u}_o(t) \left[\frac{l}{3} + \frac{8}{3} \frac{h^3}{l^2} \right]. \quad (1)$$

Where $P_i(t)$ is the inertial load at time t , ρ is the mass density, A is cross-sectional area, $\ddot{u}_o(t)$ is acceleration at the mid-span, l is the length of the mid-span and h is overhanging part of the beam. The actual bending load $P_b(t)$ can be then obtained by subtracting the generalized inertial load $P_i(t)$ from the observed top load $P_t(t)$ under the assumption of single degree of freedom system.

$$P_b(t) = P_t(t) - P_i(t) \quad (2)$$

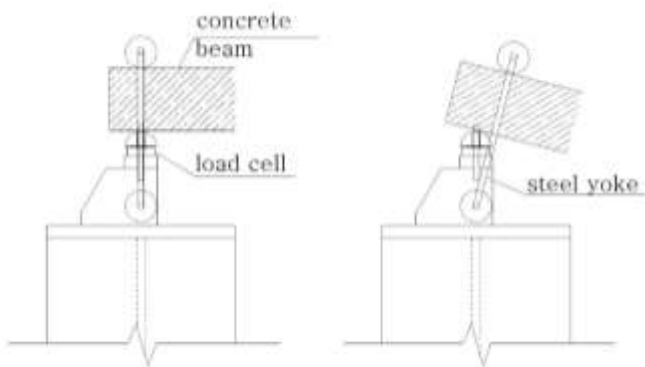


Figure 4. Instrumented supports that allow rotation of the sample and prevent an uplift of the specimen during an impact.

In some cases such as highly fibre reinforced concrete as well as concrete with continuous steel reinforcement, the data obtained from the accelerometers mounted on the specimen are heavily influenced by reflected pulses and vibrations of the whole impact machine. For this reason an impact pendulum machine presented in this paper was instrumented with load cells under supports (Fig. 4) to measure the reaction forces. These reaction forces are not influenced by the inertia of the sample, while the load measured at the top of the impactor contains the inertial forces of the specimen.

B. Instrumentation used

Measurement of dynamic properties of materials is quite complex problems and requires proper instrumentation. Inadequate data acquisition systems and low sampling rates can significantly influence the results. Two piezoelectric force sensors were used to measure the reaction forces between the support and the specimen as shown in Fig. 4. The load cells 200C50 were produced by PCB piezotronics and the maximal capacity of each load cell is 222 kN. Because these load cells are not capable of measuring tensile forces, the whole setup was prestressed to acquire these tensile forces. The acceleration of the specimen as well as accelerations of the impactor can be measured by up to five accelerometers 350B04 produced by PCB with a maximal capacity of 50,000 m/s². These accelerometers can be placed into different locations as described above depending on the experimental setup. The high resonant frequency of the instrumentation is particularly important because it can significantly influence the results. The resonant frequency of the accelerometers is higher than 100 kHz.

The data acquisition system is triggered by two diffuse electric sensors OGT 500 that also allow measuring the accurate speed of the impactor and these are located at the lowest point of the impactor trajectory. The distance between the light gates is 200 mm and their switching frequency is 2 kHz. The gates were produced by IFM Electronic. The data acquisition system consists of a signal conditioner (483C05) produced by PCB with a frequency response higher than 1000 kHz. The signal conditioner decouples the AC signal from the DC bias voltage and provides constant current excitation to the PCB sensors. The decoupled signal is then acquired by a high precision analogue DAQ board ME-5265

with 8 channels that can be sampled by rates up to 2 MHz at 16bit resolution.

III. Calibration of the machine

During the calibration process of the machine a steel specimen was used. This allowed to measure the response of the beam without the influence of fracture. Steel with yield strength of 235 MPa and modulus of elasticity of 210 GPa was used during this process. Impactor was dropped from the height of 0.3 m resulting in impact velocity equal to 2.42 m/s. The impact energy was 120 J. Both reactions exhibited almost identical signal which indicated that the sample was hit in the mid-span. During the experimental work it was found that sampling rates of 500 kHz are adequate enough.

The force measured from the load cells and the total reaction over time is shown in Fig. 5. Four accelerometers were mounted on the impactor's top to measure the acceleration of the impactor during the impact process. During the calibration process, it was found that it is very complicated to read the acceleration on the impactor due to the high stiffness of the sample and the fact that high resonance occurred. For this reason an impact attenuator was used. This approach is also adopted by other researchers [10, 11]. The attenuator was made of 4 mm thick plywood and was placed in the contact area between the sample and the impactor. The measured impact is easily readable as is shown in Fig. 6. Maximal acceleration was determined to be 3,000 m/s² and the duration of the force impulse was 2 ms.

Using Newton's second law of motion the force response gained from the impactor could be compared to the force signal gained from the load cells attached to the support reactions as is shown in Fig. 7. No signal filtering was used on the signal from accelerometers and therefore a slight deviation between the signals can be seen as shown in Fig. 7. The time difference between the maximal peak measured by the accelerometers on the impactor and the maximal force at the supports is caused by the length of the trajectory. The distance that the impulse wave needs to travel from the impact incident to the reactions is approximately 0.3 m.

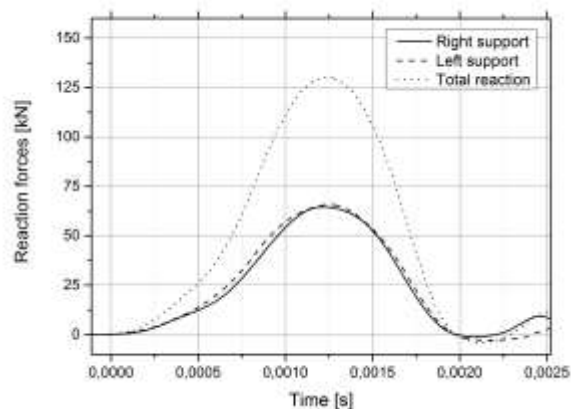


Figure 5. Response of the support reaction to impact loading of the concrete specimen.

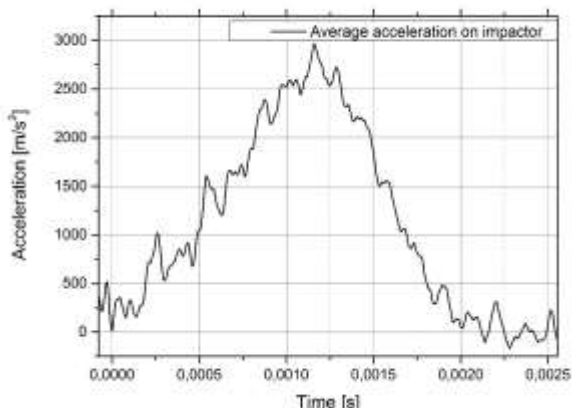


Figure 6. Response of the impactor to the impact usage of an attenuator.

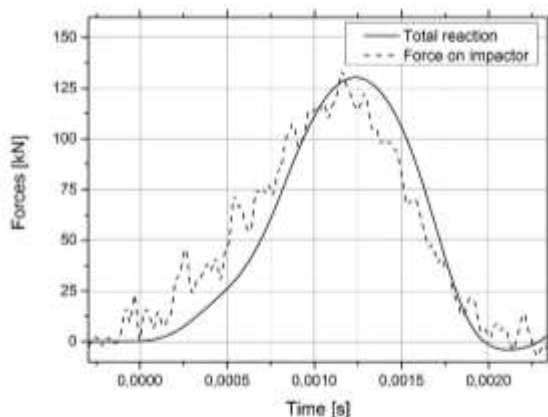


Figure 7. Response of the impactor to impact loading of the specimen compared to the support reactions with using attenuator.

The beams were tested in three point bending, where the impactor struck the beam in the middle of the deflection. The reaction forces were measured by the piezoelectric load cells. In addition, acceleration of the beam was measured in the middle of the span. Afterwards the deflection of the beam was calculated by double integration of the measured acceleration. This was also compared to the data gathered from a high-speed camera that was installed above the specimen. The sampling frequency for the camera was 8 kHz and for the piezoelectric sensors 500 kHz. No filtration was used in this particular case. The difference between the deflection obtained from the camera image analysis and from the accelerometers is shown in Fig. 8. It shows a very good correlation between those methods of measurement.

Fig. 9. shows a comparison between three point bending behavior for UHPFRC beams loaded by different loading speeds. The quasi-static loading was performed by standard hydraulic testing system. A closed loop deformation control system was used during the experimental work with a constant loading rate of 0.2 mm/min. Under the assumption of linear elastic behavior of the material, this corresponds to the strain rate of $d\varepsilon/dt = 2.2 \times 10^{-5} \text{ s}^{-1}$ at mid-span on the bottom of the specimen. The deflection was measured by two linear variable differential transformers (LVDT) positioned in the middle of the span at the sides of the specimen.

The dynamic loading was produced by the horizontal impact machine described in detail in the previous paragraphs. The impact height in this case was 70 cm and the impactor weight was 37 kg. Neglecting friction and other losses, this corresponds to 254 J of kinetic energy at the loading point. The average quasi-static strain rate was observed to be in the range of $d\varepsilon/dt = 3.2 \text{ s}^{-1}$ and according to [15] is comparable with low velocity impacts such as vehicle crash or falling rocks. The specimen didn't completely fail under the impact loading. After the initial impact, it started to vibrate and impactor continued to increase its deflection. This can be seen as a vibration response in the Fig. 9 for the dynamic loading curve.

iv. Impact Resistance of Concrete

After the successful calibration of the machine, the impact resistance of ultra high performance fiber reinforced concrete (UHPFRC) was measured. For the purpose of this experimental work, beams with the dimensions 100×100×400 mm were casted using the UHPFRC mixture with 2% of steel fiber reinforcement. The mixture components as well as the mixing procedure is described elsewhere [13, 14]. The basic UHPFRC mechanical properties, are summarized in Tab. 1.

TABLE I. BASIC MECHANICAL PROPERTIES OF UHPFRC

Property	UHPFRC
Fiber type	0.15×13 mm
Workability – spread	225 mm
Compressive strength	150 MPa
Flexural strength	40 MPa
Direct tensile strength	10 MPa
Modulus of elasticity	56 GPa

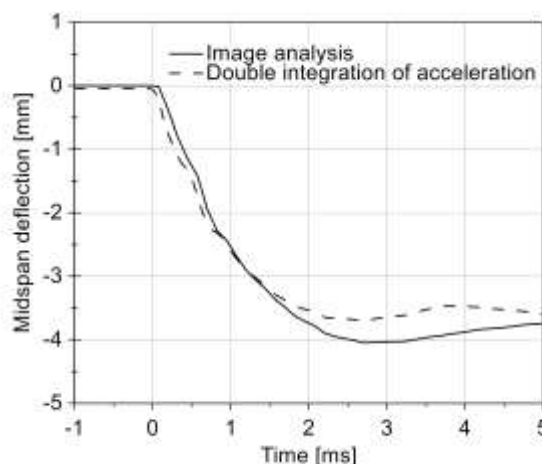


Figure 8. Beam deflection in time as obtained from acceleration and image analysis

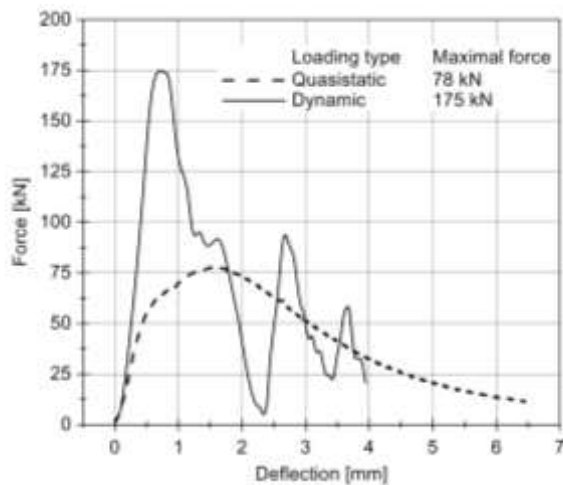


Figure 9. Force deflection diagram for UHPFRC beams loaded by different speeds.

v. Conclusions

A novel design for impact testing machine of concrete specimens was presented in this study. It was demonstrated that it is more convenient to have horizontal impact in order to avoid so called double hit and also to provide more comfortable space for instrumentation of the sample. Design of the impact machine is highly modular and it is very simple to change its configuration for testing the slabs. Steel yokes were successfully applied in order to avoid uplift of the specimen. After comparing several impact tests sampled by different rates, it was stated that 500 kHz sampling frequency is sufficiently enough for measuring response of materials such steel or concrete even in case without any attenuator. In the case of attenuator usage, the sampling frequency can be as low as 10 kHz. It was also established that flexible cable guides should be provided for connection of the impactor to the rest of the machine in order to avoid eigen frequencies of the guide system similar to the eigen frequency of the sample. Samples made of UHPFRC were loaded by impact and its three point bending response was compared to beams loaded by standard loading machine. It was found that the maximal force during impact loading is more than double compared to the maximal force measured at quasi-static conditions. However, this conclusion needs to be confirmed during further research on a statically more significant number of samples. In the future research the authors plan to test different types of concrete under impact using the described machine. The loading strain rate will be varied by using an attenuator and different impact heights. This should lead to the deeper understanding of concrete behavior under impact loading at intermediate strain rates.

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