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# NONLINEAR FINITE ELEMENT ANALYSIS OF IMPACT BEHAVIOR OF CONCRETE BEAM

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**Abstract-** The least well known loading type is the impact loading that are affecting on to RC structures. Several impact tests have been used to demonstrate the relative brittleness and impact resistance of concrete and similar construction materials. However, none of these tests has been declared to be a Standard test, at least in part due to the lack of statistical data on the variation of the results. In this study; total ten beam specimens at which five of them are manufactured from normal concrete compression strength without reinforcement are manufactured. Remaining five had high concrete compression strength. These specimens are tested under the impacts loading that are applied by dropping constant weight hammer from five different heights. The acceleration arises from the impact loading is measured against time. The change of velocity, displacement and energy is calculated for all specimens. The failure modes of the specimens with normal and high concrete compression strength are observed under the loading of constant weight impact hammer that are dropped from different heights. A finite element model that is made by using ABAQUS software is used for the simulation of experiments and model gave compatible results with experiments.

**Key Words-** Impact, Concrete, ABAQUS

## 1. INTRODUCTION

Concrete is the most widely used construction material in the world. Its consumption is around 10 billion tons per year, which is equivalent to 1 ton per every living person [1]. A variety on loads is applied to concrete all along its economical life. These loads can be separated into two types namely static and dynamic loads. Dynamic loads include explosive shocks, impact of a bullet or rocket, wind, earthquakes, impact of ships on to legs are RC bridges or petrol platforms, drop of rocks on to building that are constructed of avalanche regions and machine vibrations. The one among the dynamic loads at which very limited amount of investigation are done is the impact loading. Although the magnitude and application time of the impact loading can not be known exactly like the static loadings the instantaneous magnitudes can reach larger values than the other loading types [2, 3]. The impacts behaviors of basic structure material like steel and concrete got importance with the technological improvements. For example the loading during the nuclear reactions at nuclear centrals can reach very high magnitudes suddenly. Structures that have military significantly or strategic importance and very populated structures should be design according to impact loadings.

Impact testing are concentrates on to one of the basic structural material namely steel. But due to increase in active use of concrete, the impact behavior of the concrete started to gain importance. There is no established standards or methods for impact testing up to nowadays' studies [4-7]. But ASTM E 23 regulations improved the test setup performance significantly and gave good starting points for the limits of impacts experiments [8]. When the experimental impact studies at literature are investigated, they are categorized in to two main segments. One of them depends on the investigation on specimens under impact loads that are applied by test equipments. These types of studies are concentrated on mostly steel materials. The other studies use equipment with mechanism that drops masses from height. This method is used mostly for the concrete impact testing [9, 10]. Several impact tests have been used to demonstrate the relative brittleness and impact resistance of concrete and similar construction materials. However, none of these tests has been declared to be a standard test, at least in part due to the lack of statistical data on the variation of the results.

There are studies investigating impact behaviors of concrete when the additive materials such polypropylene or steel fibers are added to concrete [11, 12]. These studies showed that additive are affected the impact strength of the concrete positively. But these fibers made handling of the concrete different increased the cost. In addition when the volume of the concrete increased, the homogeneous distribution of additives became hard. As a result the property of the concrete differs according to distribution. For these reasons, only standard mixtures with increased concrete compression strength are used for this experimental study.

In this study, the impact behavior of the high compression strength concrete is investigated. The effect of increase in concrete strength on impact behavior is analyzed. Totally ten unreinforced RC beam specimen are manufactured. Five of them are manufactured with normal and the other with high compression strength concrete. All of them are tested under free falling hammer. The change in concrete compression strength, the number of hammer drop, acceleration distribution and failure behaviors are the investigated parameters. Velocity, displacement and dissipated energy values are calculated and compared by using measurement for the specimens. After completing test of the specimens, ABAQUS [13] finite element software is used for making simulation of the some test cases. Results of the experiments and FEM analyzes are compared and a model is established for giving a preliminary idea to designer about the simulation of impact behavior.

## 2. TEST SPECIMENS AND MATERIALS

RC beam without reinforcements are manufactured for the experimental study with dimension 710x150x150 mm. Total 10 specimen prepared and half of them have normal and the remaining ones have high strength. The geometrical dimensions for specimen with normal and high strength are identical and are given in Figure 1.

Impact loading is applied by special test equipment that drops weight from adjusted heights. A constant weight is dropped from five different heights on to specimens. Measurements are taken from specimens by dropping weight from starting lower heights and then heights are increased. Impact loading is applied up to failure of the specimens and behaviors are observed. Specimen with normal strength are tested by dropping hammer from height 300 mm and for each specimen this height increased 50 mm up to 500 mm. Same loading procedure is applied to high strength specimens. The properties of the specimens are summarized at Table 1.

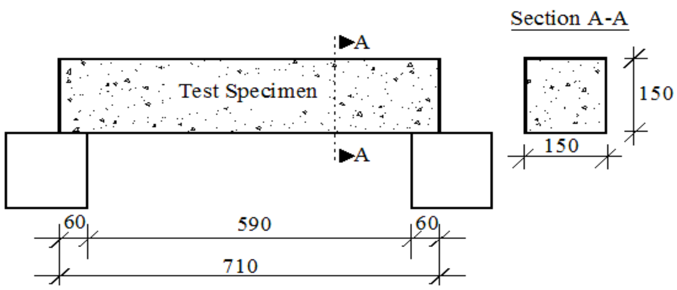



Figure 1. Dimensions of test specimens

Table 1. Test specimens

| Specimen No | Specimen Dimensions (mm) | Concrete Compression Capacity | Weight Drop Height(mm) |
|---|---|---|---|
| 1 | 710x150x150 | Normal Strength Concrete | 300 |
| 2 | 710x150x150 | | 350 |
| 3 | 710x150x150 | | 400 |
| 4 | 710x150x150 | | 450 |
| 5 | 710x150x150 | | 500 |
| 6 | 710x150x150 | High Strength Concrete | 300 |
| 7 | 710x150x150 | | 350 |
| 8 | 710x150x150 | | 400 |
| 9 | 710x150x150 | | 450 |
| 10 | 710x150x150 | | 500 |

Concrete compression strength of the specimens are determining from the compression test of cylindrical specimens with dimensions 150x300 mm. Five from each normal and high strength specimens are cast together for preventing differences in compression strength. Five cylindrical pieces from each specimen are tested and the results are summarized at Table 2.

Table 2. Concrete Compressive Strength of Specimens

| Specimen No | Concrete StrengthType | Concrete Strength (MPa) |
|---|---|---|
| 1 | Normal Strength Concrete | 24.86 |
| 2 | | 24.36 |
| 3 | | 24.72 |
| 4 | | 25.00 |
| 5 | | 24.58 |
| 6 | High Strength Concrete | 45.23 |
| 7 | | 45.89 |
| 8 | | 46.02 |
| 9 | | 45.78 |
| 10 | | 45.56 |

According to results the correlation between the concrete compression strength of the specimen are very high. Variation and standard deviation of the specimens with normal concrete compression strength are 0.06 and 0.25. The same parameters are calculated for the high strength specimen 0.10 and 0.31. The weight and mixture ratios of the ingredients for the concrete that are used for normal and high strength specimens are given at Table 3.

Table 3. Concrete mix properties

| Normal Strength Concrete | | |
|---|---|---|
| Materials | Weight | Weight |
| Cement | 22.5 | 20.9 |
| Gravel (7-15 | 40 | 37.3 |
| Sand (0-7 | 30 | 27.9 |
| Water | 15 | 13.9 |
| High Strength Concrete | | |
| Materials | Weight | Weight |
| Cement | 42.3 | 18 |
| Silica Fume | 4.23 | 1.8 |
| Gravel (7-15 | 44.65 | 19 |
| Sand (0-7 | 122.20 | 52 |
| Plasticizer | 0.48 | 0.2 |
| Water | 21.15 | 9 |

Two type of aggregate are used for the mixture with the size of 0-7 mm and 7-15 mm. KPÇ 42.5 Portland cement is used for concrete production. Two different additives namely plasticizer and silica fume are added to mixture as 1% and 10% of concrete weight for obtaining high strength, respectively.

## 2.1. Test Results

Impact loading is applied to specimens from 5 different heights up to failure by using constant weight (5.25 kg) hammer. Internal effects after each drop are measured with accelerometers. Crack initiation and propagation, the number of the hammer drop, acceleration-time relation and specimen's general behaviors are observed during the experiments.

The damage styles and failure modes are differ for the normal and high strength concrete compression strength specimens. Due to the fact that the ductility of the normal strength specimens are greater than the high strength ones the number of the hammer rebound is less than the high strength specimens. Specimen 3 and 8 are the specimens that are tested by dropping hammer from 400 mm and specimen 3 is manufactured with normal concrete while specimen 8 is manufactured with high strength concrete. The figures 2 and 3 are taken after failure of the specimen 3 and 8, respectively.

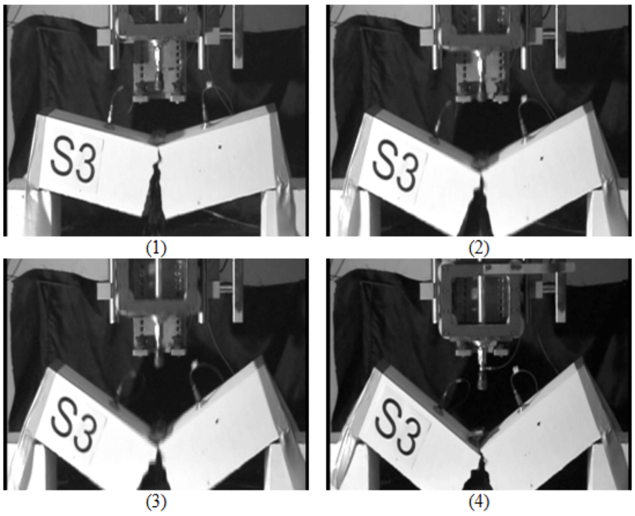



Figure 2. Failure Drop Cycle of Specimen 3

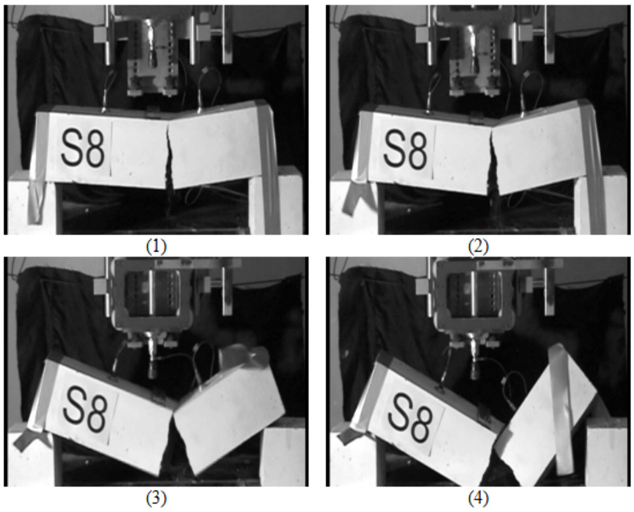



Figure 3. Failure Drop Cycle of Specimen 8

### 2.2. Acceleration, Velocity and Displacement Behaviors of Specimens

Two symmetrical acceleration measurements are taken from the beam for determining internal behaviors against impact loading. Time dependent velocity and displacement graphs are obtained by using acceleration graphs. Velocity and displacement are calculated by taking integration of the acceleration with time.

### 2.3. Absorbed Energy Capacities of Specimens

It is assumed that all of the potential energy lost by the hammer during drops is transferred to internal deformation energy by the tested beams while calculating the energy capacities of the specimens and no energy lost is occurred. In addition linear elastic material assumption is made during calculations and moment of inertia value without any crack is used. While calculating the stored deformation energy of the specimens, energy that is stored by the influence a bending moment is taken into account and energy that is formed due to shear forces is neglected.

**2.4. Analytical Study**

Investigated literature emphasized that generalization of the result can be done if large number of experiment are done and the large amount of data is required for this purpose. But the design is the laboratory test system and specimens took time and required lots of investment. For these reasons authors though that a finite element model that is verified with experimental results can gave a preliminary idea to designer and became helpful. For this purpose, a simulation is done by using ABAQUS finite element software for the investigated experimental study. The FEM and experimental results are compared and the level of consistency between them is investigated. Acceleration and energy values of both experimental and FEM are tabulated at Table 4 and Table 5 for the drop at which maximum acceleration is measured for the comparison.

ABAQUS software is used for FEM modeling in this study. Due to its properties such as it has dynamic modeling capability and there are lots of elements type with different material modes in the library. Linear-elastic material model is used for the specimen and the hammer. Impact loading is a dynamic loading; therefore loading is started from a small magnitude and with small time increments increased up to its final value nonlinearly. The dimensions of the specimen and setup and supporting condition are modeled like in the experimental study. Snap shot of the FEM mesh is given at Figure 4. While the size and refinement of the FEM mesh determined, a finite mesh size is chosen and then refinement is done up to reaching a threshold between the results of two consecutive runs. If the results of two run is close enough, refinement is stopped. The experimental and FEM results such as acceleration and energy absorption values, stress distribution and failure modes are compared.

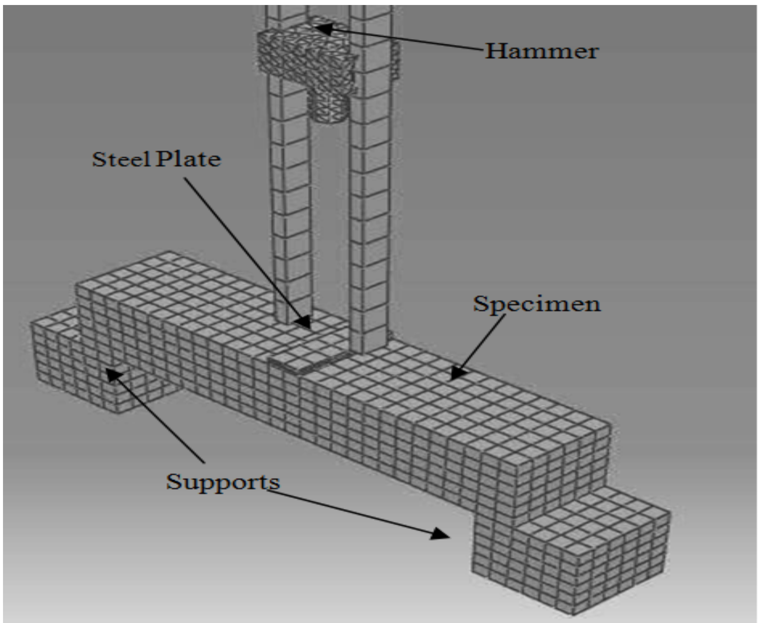
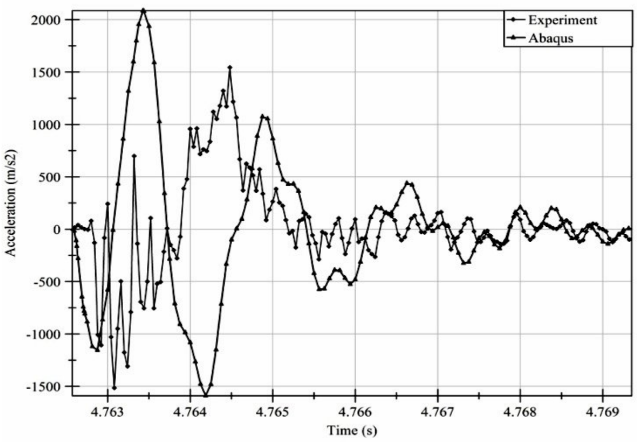
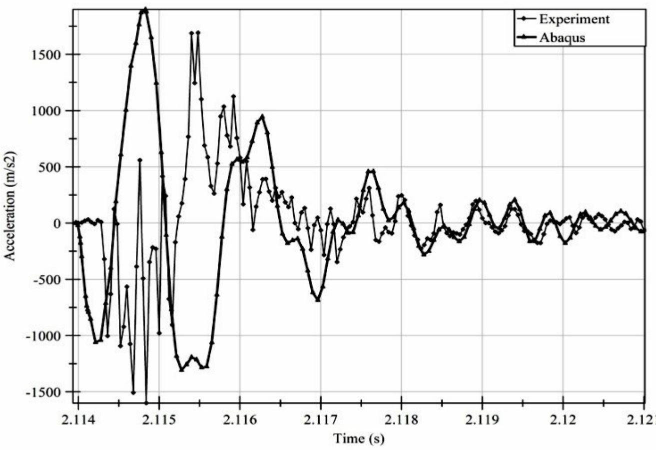



Figure 4. Finite Element Mesh of Specimens

Acceleration graphs that are obtained from experiments and FEM analyze for Specimen 3 with normal strength concrete and Specimen 8 with high strength concrete is given at Figure 5 for compression. When the graphs are investigated, both results are seemed to be consistent with each other. But as can be seen from Table 6, there is 45% and 89 % difference between experiments and FEM result at maximum and minimum acceleration value, respectively. Authors thought that this difference between acceleration values can be due to linear elastic material model that is used at FEM and assumption that are made during impact modeling. In addition, stress distribution graphs that are obtained from FEM modeling and experimental damage and failure planes are compared. Stress distributions that are obtained from FEM analyses for specimen 3 with normal strength concrete and Specimen 8 with high strength concrete are given at Figure 6.

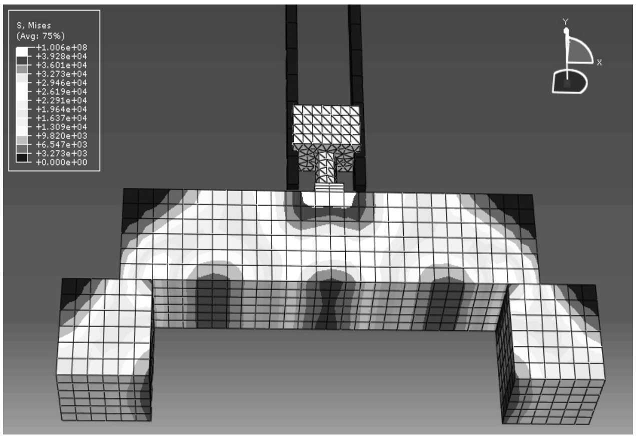



a) Experimental and Finite Element Model Acceleration Graphs of Specimen 3

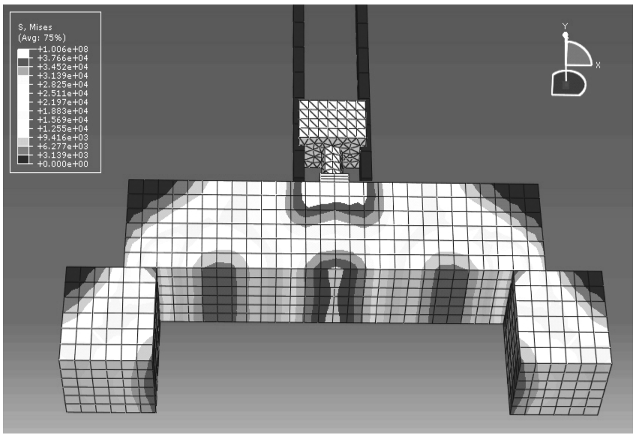



b) Experimental and Finite Element Model Acceleration Graphs of Specimen 8

Figure 5. Comparison of Experimental and Finite Element Model Acceleration for Specimen 3 and Specimen 8 at Maximum Acceleration Drop Cycle




a) Stress Distribution Contour of Specimen 3




b) Stress Distribution Contour of Specimen 8

Figure 6. Stress Distribution Contour for 400 mm Drop Height

FEM analyses are made for the case at which hammer is dropped from 400 mm. When the stress distribution graphs of FEM analyses are investigated, after the impact is occurred a sudden stress concentration is observed and this residual stress is remained on to the specimen. Due to differences at the elastic modulus of the materials, the stress at the hammer is significantly larger than the stress at specimen. A crack line is observed that the specimens due to cyclic application of stress concentration that is created by the impact loading. Experimental damage and crack lines are showed similarities with the ones that are obtained from FEM. Damage and failure plane at experiments are occurred at the regions where stresses are concentrated. Especially the failure planes of specimens with high strength concrete are one consistent with FEM analyses than the specimens with normal strength concrete.

As can be seen from the Table 4 and Table 5 the difference between the experimental and FEM energy dissipations can be as high as 3 times. This difference stem from the usage of the linear elastic material model instead of anisotropic and nonhomogeons concrete and assumptions that are made at the energy calculation can not simulate the elasto-plastic real impact situation sufficiently.

Table 4. Comparison of Experimental and Finite Element Model Acceleration for Measured Maximum Acceleration Drop Cycle

| No | Acceleration (m/s$^2$) | | | |
|---|---|---|---|---|
| | Experimental | | ABAQUS | |
| | Maximum | Minimum | Maximum | Minimum |
| 1 | 2555.21 | -2677.34 | 1761.77 | -1413.05 |
| 2 | 1298.94 | -1349.27 | 1943.87 | -1480.64 |
| 3 | 1544.00 | -1515.74 | 2085.49 | -1590.42 |
| 4 | 1864.88 | -2088.45 | 2171.4 | -1785.51 |
| 5 | 1550.91 | -2537.55 | 2294.82 | -1743.96 |
| 6 | 1461.77 | -1225.96 | 1630.26 | -1160.83 |
| 7 | 1955.03 | -1432.90 | 1793.13 | -1209.86 |
| 8 | 1691.05 | -1600.60 | 1898.27 | -1307.5 |
| 9 | 1453.94 | -1900.59 | 1980.32 | -1501.75 |
| 10 | 1386.55 | -2677.35 | 2121.21 | -1529.29 |

Table 5. Comparison of Experimental and Finite Element Model Energy Capacity of Specimens for Measured Maximum Acceleration Drop Cycle

| Experimental/ ABAQUS Acceleration Ratio | | Energy (J) | | Experimental/ ABAQUS Energy Ratio |
|---|---|---|---|---|
| Max. | Min. | Experimental | ABAQUS | |
| 1.45 | 1.89 | 1.346 | 3.741 | 0.36 |
| 0.67 | 0.91 | 1.769 | 4.232 | 0.42 |
| 0.74 | 0.95 | 2.649 | 4.826 | 0.55 |
| 0.86 | 1.17 | 1.742 | 5.649 | 0.31 |
| 0.68 | 1.46 | 3.159 | 6.221 | 0.51 |
| 0.90 | 1.06 | 1.295 | 3.288 | 0.39 |
| 1.09 | 1.18 | 1.689 | 3.702 | 0.46 |
| 0.89 | 1.22 | 2.090 | 4.293 | 0.49 |
| 0.73 | 1.27 | 2.219 | 5.142 | 0.43 |
| 0.65 | 1.75 | 1.797 | 5.510 | 0.33 |

## 3. CONCLUSIONS AND RECOMMENDATIONS

The purpose of this study is to investigate the behavior of RC beams under the impact loading that is applied by the free fall of hammer. The investigated parameters are the drop height and concrete compression strength. Specimens with two different concrete compression strength are tested with dropping hammer from five different heights. Evaluations that are made after experiment can be cited as the number of drop that causes failure, acceleration velocity, displacement, time, energy capacities, crack arrangement and failure modes. In addition simulation of the experimental study is made under the light of the obtained result by using FEM software. FEM and experimental results are compared and the consistency of the FEM to experiment results is investigated. The results of this study can be cited below as follows;

The behavior of the concrete, which is widely used in the world as a construction material, against impact loading is not known well and there is no standard test procedure for this loading type. Due to limited amount of experimental data and lack of standard test procedure, generalization became very hard. For this reason, authors thought that experimental data are significantly important. In this experimental study, free falling hammer that is widely used in the literature for investigating impact behavior of concrete is used as an experimental setup.

One of the important parameters for impact is known to be the number of drops and this is changed with the concrete compression strength. It is seen that the number of drops for the specimens with high concrete compression strength is significantly more than that of specimen with normal concrete compression strength. But when the drop height is increased, the difference between the specimens with high and normal concrete compression strength is reduced. For example at 500 mm drop height both specimens with high and normal concrete strength are failed with 2 drops.

The failure modes damage behavior of the specimens with high and normal concrete strength is showed differences under the impact loading. The number of the hammer rebounds on the specimens with normal concrete strength is less than the specimens with high concrete strength due to high ductility of the specimens with normal concrete strength.

When the failure surfaces of the specimens with normal strength concrete are investigated, it is seen that aggregate distribution is affecting the failure scheme and failure plane is breaking the aggregate and matrix by following their interfaces. As a result failure is occurred due to separation of aggregate from matrix surfaces. The cracks are branching and propagating through the aggregate and different aggregate distribution of the specimens is caused to have differed failure planes. When the failure surfaces of the specimens with high strength concrete are investigated, the failure occurred at both aggregate and matrix. It and the distribution of the aggregate can not affect significantly the failure plane. The failure planes of all high strength concrete specimens are formed rarely with the same topology. All of them are perpendicular to beam axis.

Maximum acceleration drop ratios are more than the minimum acceleration ratios for both specimens with normal and high strength concretes. In addition, acceleration drop at specimens with normal strength concrete are less than the specimens with high strength concrete. These findings are the same for all drops at when maximum and minimum acceleration measured and failure occurs.

Average calculated energy for the specimens with normal concrete strength is 17% larger than that of specimens with high concrete strength for the drop at which maximum acceleration is measured. This is the case because specimens with normal concrete strength are made larger displacement and they have more ductility. For this reason, drop at which maximum acceleration is measured they have larger energy than the specimens with high concrete strength. But the number of the drops that the failure is observed at high strength concrete specimens more than that of normal strength concrete ones. As a result cumulative dissipated energy of the specimens with high strength concrete is larger than that of normal strength concrete specimens.

Acceleration-time graphs and stress distributions that are obtained from FEM software ABAQUS are compared with the experimental results. FEM have some crucial assumptions. Due to the complexities at the FEM are experimental setup, specimens and the nature of physical impact loading, models that are used in this study have some uncertainties and it is hard to model. If an anisotropic and non linear model is prepared for the non homogeneous concrete, more accurate result can be obtained. In this study, this nonlinear nature of the experimental specimen is neglected for gaining runtime. Extra attention is paid for the modeling of impact incidence and non linear dynamic model is prepared. FEM in this study can only be used for giving prior idea for the designer about the impact behavior.

## 4. REFERENCES


1. T.S. Nagaraj, S.G. Shashiprakash, B.K. Raghuprasad, Reproportioning concrete mixes, ACI Mater. J. 90 (1) (1993) 50–58.
2. Goldsmith, W., Impact: The Theory and Physical Behavior of Colliding Solids", London Edward Arnold Limited, 145-240 (1960).
3. Murtiadi, Surwayan. , "Behavior of high-strength concrete plates under impact loading", Master Thesis, Faculty of Engineering and Applied Science Mernorial University of Newfoundland, (1999).
4. Kishi N, Konno H, Ikeda K, Matsuoka KG. Prototype impact tests on ultimate impact resistance of PC rocksheds. Int J Impact Eng 2002;27(9):969–85.
5. Ong KCG, Basheerkhan M, Paramasivam P. Resistance of fibre concrete slabs to low velocity projectile impact. Cement Concrete Composites 1999;21(5–6):391–401.
6. Mindess S, Cheng Y. Perforation of plain and fibre reinforced concretes subjected to low-velocity impact loading. Cement Concrete Research 1993;23(1):83–92.
7. Barr B, Baghli A. A repeated drop-weight impact testing apparatus for concrete. Magazine Concrete Research 1988;40(144):167–76.
8. Siewert, T. A. , Manahan, M. P. , McCowan, M. P. , Holt, J. M. , Marsh, F. J. , Ruth, E. A. , "The history and importance of impact testing", ASTM, (1999).
9. Banthia, N. P. , "Impact resistance of concrete", PhD Thesis, The University of British Columbia, (1987).
10. Bull, P. H. , Edgren, F. , "Compressive strength after impact of CFRP-foam core sandwich panels in marine applications", Composites: Part B , 35: 535-541 (2004).
11. Atef Badr, Ashraf F. Ashour, Andrew K. Platten. Statistical variations in impact resistance of polypropylene fibre-reinforced concrete. International Journal of Impact Engineering 32 (2006) 1907–1920.
12. M.C. Nataraja, T.S. Nagaraj, S.B. Basavaraja. Reproportioning of steel fibre reinforced concrete mixes and their impact resistance. Cement and Concrete Research 35 (2005) 2350 – 2359.
13. ABAQUS/Explicit User Manual, Version 6.7.