Experimental investigation of reinforced concrete beams with and without steel fiber under explosive loading

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The aim of this study is to determine the energy absorption capacities of the reinforced concrete (RC) beams of the same concrete class and to obtain the performances of the steel-fiber added beams according to the damage characteristics obtained by the explosive loading. In this paper, effects of blast load on the RC beams samples with and without steel fiber have been investigated. First, the compressive strength of concrete made with and without steel fiber have been measured. Second, the load carrying capacities of the RC beams produced with and without steel fiber are determined by two point loading test. Last, the damage levels under explosive loading applied on the RC beams produced with and without steel fiber have been observed. The results show that RC beams made with steel fiber is damaged less in blast loading than that of conventional RC beams. The results also show that the expression used in calculating the amount of the explosive material needs to be revised.

Keywords: Steel fiber added concrete, Steel fiber added reinforced concrete beams, Blast loading, Explosion, Toughness

Generally, explosion is an event that occurs with release of a big amount of energy in a fast and sudden way. While the energy formation of conventional explosives such as Trinitrotoluene (TNT) is caused by re-arrangement of atoms, the energy released by nuclear explosions is caused due to structuring of protons and neutrons in atom nucleus. Explosion, in civil engineering, is an extraordinary type of dynamic load to which the building is exposed additional to custom loads. Custom design methods does not satisfy the design requirement of the buildings that are exposed to blast loads and lead to uneconomical results in design of the structural systems. Also, the difficulties in experimental set-up limit the number of experimental studies on the effect of the explosion on the building. Today’s civil or military structures may face with the blast loads that may arise due to various reasons. Another type of loading, which may be faced, is the collision of vehicle to a structure. The safety of military and civil buildings with strategic importance has to be increased especially against blast loading.

Strength and other mechanical properties of concrete has been tried to be improved with the help of various additives. As an additive, various chemicals have been used besides various sizes of steel fibers. It is known that when the compressive strength of concrete increases, the concrete absorbs less energy during the failure. However, when steel fiber is added to the concrete, the concrete has higher energy absorption capacity, less crack risk and higher durability. Also, the concrete with steel fiber shows more ductile behaviour during the failure. Due to these properties, the demand of the concrete with steel fiber increases.

Concrete with steel fiber are commonly used in mine and tunnel linings, slab and floors, rock slope stabilization, repair materials, shell domes, refractory linings, dam construction, composite metal decks, aqueduct rehabilitation, seismic retrofit, marine structure repair and rehabilitation, fire protection coatings, concrete channel pipes and RC frames due to their high energy absorption capacity

Size of the sample, loading speed and experimental set-up affected toughness of concrete. Optimum steel fiber dosage was stated as 30-40 kg/m³ to minimize the concrete cracks and a general empirical expression was defined for crack width with respect to steel fiber dosages. It was also reported that the steel fiber has positive contributions to the mechanical properties of the concrete. Moreover, the use of steel

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fiber led to a decrease crack patterns in failure and the concrete showed a more regular cracking behaviour. Optimum fiber dosage changes when the type steel fiber changes. If the steel fiber dosage is higher, there is a decrease in compressive strength of the concrete. The reason is that addition of steel fibers in a higher rate led to form lumpy mass of concrete, weak areas and air spaces within the concrete during the mixing process.

Researches on blast loading have started after World War II. The damages would decrease if blast loading is considered as inconvenient loads in calculations for buildings with strategic importance.

One approach of protecting structures is to strengthen the concrete by applying internal reinforcement e.g., fiber reinforced concrete.

The other approach is to reduce the damage to concrete structures by protecting them with external elements. For engineering design, empirical formulae have been proposed for the minimum thicknesses of the target to prevent scabbing and perforation, respectively, and for estimating the penetration depth for thick targets in order to quantify the local damage of the target. In doing this the effects of the overall structural response on these local effects are generally neglected. The local failures of a concrete target subjected to missile impact include spalling, scabbing, penetration, cone cracking and perforation.

Another approach is to describe full-scale field explosion tests on protected and unprotected concrete slabs. In that study, time-dependent measurements of the response of the concrete slabs to the blast wave loads were successfully recorded using a variety of measurement devices.

The objective of this study was to determine the energy absorption capacities of the RC beams of the same concrete class and to obtain the performances of the steel-fiber added beams according to the damage characteristics obtained by the explosive loading. Another objective of this study is to evaluate the Hauser expression calculating the amount of the explosive material.

The study had three stages. The first stage is about determining the concrete class for the cylindrical concrete specimens with steel fibers. In the second stage, the energy absorption capacities of the RC beam members of the same concrete class were calculated based on the load-displacement diagrams of the experimental studies. The last stage is about observing the damage levels under explosive loading applied on the RC beams produced with the same concrete and reinforcement details. For this purpose, the restraint conditions were set identical to be able to compare the performances of the RC beams under vertical and explosive loadings.

Effects of Explosive Materials

An explosive or an explosive mixture is a mixture of chemicals that gives a big amount of heat and gas when triggered by heat, stroke, friction or shock. This chemical reaction, which spreads by itself and radiates heat, is called explosion.

When the explosive materials are exploded very close to the building, explosion is called as contact explosion. Contact explosion causes local effects that should be considered in determination of thickness of structural element. Explosion in outer surface of the RC element causes material flow, crater formation on the surface and an increase in compressive stress. Shock waves, which spread as pressure, hit the concrete and then reflect. This means that compressive stress turns into tensile stress. Since the tensile strength of the concrete is lower than its compressive strength, tensile cracks occur in the concrete.

Some amount of energy is required to break the construction elements in a certain size and to move them to a certain distance. The explosion parameter that defines this energy is called specific charge. In other words, it is the amount of explosive consumed per cubic meter of the reinforced concrete.

Hauser equation to determine the amount of energy per cubic meter of the concrete is shown in Eq. (1).

\[ L = W^3 C D \quad \ldots(1) \]

For outer fill, \( W \) is thickness of the target to be exploded. For inner fill, if the explosive is placed at the middle of the target to be exploded, \( W \) is the half of the thickness of the target, \( C \) is the specific explosive amount and \( D \) is the tamping coefficient.

Experimental Procedure

Experimental study was carried out on the concrete specimens and RC beams with or without steel fibers. Blast experiments with explosives were carried out on RC beams with various dosages of steel fiber.
Materials
Concrete strength class of C30 was used. For the cylinder concrete samples with steel fiber, (water/cement) ratio was 0.5 and slump values were within the range of 150 mm ± 20 mm. Mix design of the materials used for 1 m³ of concrete was shown in Table 1.

Dramix RC 80/0.60 BN type steel fiber with \( l_n = 60 \) mm in length and \( d = 0.75 \) mm in diameter was used in this research. Tensile strength of steel fiber was 1050 N/mm² at minimum. Steel fiber was added into the transmixer with speed of 20 kg/min. The mixture was rotated at maximum speed for 5 minutes\(^{17,18} \).

Experiments on concrete specimens
Six concrete cylindrical samples with steel fiber were produced for each dosage of 30 kg/m³ and 60 kg/m³, 12 pieces in total. Also, six concrete cylinder samples without steel fiber were produced for comparison. The cylindrical concrete samples were tested at 28 days. During the test, displacement values of the samples were taken at a load increment of 20 kN and transferred to computer. Average stress-strain curve was obtained from these values. A typical stress-strain curve was shown in Fig. 1.

The random distribution of steel fibers inside concrete causes a decrease in the strength of the concrete\(^{19-21} \). Failure loads were determined for the cylinder concrete samples with or without steel fiber. Also, modulus of elasticity and toughness of the concrete samples were determined in compliance with\(^{22,23} \).

Experiments on reinforced concrete beams
Three RC beams with steel fiber in dosages of 30 kg/m³ and 60 kg/m³ were produced in size of 2000 × 300 × 300 mm. Also, three RC beams samples without steel fiber were produced for comparison. The reinforcement plan is given in Fig. 2.

Two-point loading was applied to the RC beams during flexural test. Concrete strength class of C30 and reinforcement class of S420 was used in calculation of compressive strength of the reinforced concrete with steel fiber\(^{17,18} \). Reinforcement percentage of 0.5% was selected to have a ductile failure. RC beams were tested to the failure in the loading frame after they were held in proper curing conditions for 28 days, as shown in Fig. 3.

<table>
<thead>
<tr>
<th>Materials</th>
<th>Quantity (kg/m³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water</td>
<td>180</td>
</tr>
<tr>
<td>Cement CEM II/B-M 42.5R</td>
<td>355</td>
</tr>
<tr>
<td>Limestone</td>
<td>457</td>
</tr>
<tr>
<td>Sand</td>
<td>448</td>
</tr>
<tr>
<td>Thin Balast</td>
<td>355</td>
</tr>
<tr>
<td>Big Balast</td>
<td>530</td>
</tr>
<tr>
<td>Plasticizer</td>
<td>3.5</td>
</tr>
<tr>
<td>Steel Fiber</td>
<td>0, 30, 60</td>
</tr>
</tbody>
</table>

Fig. 1— Stress-Strain curves for cylinder concrete samples

Fig. 2— Reinforcement plan
A displacement meter was installed at the middle of the beams and the displacement values ($\delta$) were transferred to computer to obtain load-displacement curves, as shown in Fig. 4.

Experiments on blast loadings

Two RC beams with the steel fiber dosages of 30 kg/m$^3$ and 60 kg/m$^3$ were produced in the size of 2000 × 300 × 300 mm. Two RC beams without steel fiber addition were produced for comparison. RC beams with or without steel fiber addition were tested to the failure as shown in Fig. 5.

10 cm tamping was made at every side of the explosives with specially produced sandbags. This led to use of one third of the amount of explosive calculated by Hauser equation. According to Hauser equation, 1000 g of explosives was needed per cubic meter of RC beams with or without steel fiber.

Electrical capsules were used to detonate the Anfo in the experiments. For a reliable explosion, each capsule was provided with adequate electrical energy from a power supply. Main connection wires in detonation circuit provided electrical energy to capsules in consecutive manner. Then, capsule
transforms this energy to explosion. Number and resistance of the capsules, and length and resistance of wire were taken into the account in the design of detonation circuit. Before the explosion, detonation circuit was short-circuited. However, during explosion, short circuit and contact of wires with the ground were prevented. Capsules used in the explosion were provided to reach the explosion holes at least from two points. End of fuse was cut at an angle of 45° and fuse was squeezed by special pliers from the neck of the capsule at a length of 5 mm. Explosion fuse was ignited by turning ignition handle and explosion occurred. In order to observe the damage levels, experiments were also made with the amount of explosive of 750 g and 500 g per beams, as shown in Fig. 6.

**Results and Discussion**

Concrete cylinder samples with steel fiber showed a typical pattern of failure. Although loading was continued after the ultimate load, concrete samples were not observed to break and scatter excessively. Compressive strength and modulus of elasticity of concrete specimens with steel fiber in dosages of 30 kg/m³ and 60 kg/m³ were shown in Table 2.

Compressive strength of the concrete specimens with steel fiber in dosages of 30 kg/m³ and 60 kg/m³ was less than that of concrete cylinder samples without steel fiber. The random distribution of the steel fibers inside the concretes with steel fibers decreases the strength of the concrete. Modules of elasticity of the concrete without steel fiber and with steel in dosage of 30 kg/m³ and 60 kg/m³ were determined as 32950 N/mm², 32200 N/mm² and 32050 N/mm², respectively. The modulus of elasticity of the concrete samples with steel fiber in dosages of 30 kg/m³ and 60 kg/m³ was very close to each other.

Flexural test results of the RC beams without steel fiber and with steel fiber in dosage of 30 kg/m³ and 60 kg/m³ were shown in Table 3.

![Fig. 6](image_url)—Reinforced concrete beam explosion tests with steel fiber addition in dose (a) 0 kg/m³, (b) 30 kg/m³ and (c) 60 kg/m³.
The ratio of experimental and theoretical ultimate load was determined for the RC beams without steel fiber and with steel fiber in dosage of 30 kg/m³ and 60 kg/m³ as 1.45, 1.90 and 2.06, respectively. Therefore, average increase in the ratio of experimental and theoretical ultimate load in the RC beams with steel fiber in dosage of 30 kg/m³ and 60 kg/m³ compared to the RC beams without steel fiber was about 31% and 42%, respectively. This also shows that load carrying capacity of the beam increased only 11% although amount of steel fiber was doubled.

Load-displacement curves were obtained according to mid-point displacements of the RC beams as shown in Fig. 4. Average energy absorption capacity of the RC beams with or without steel fiber was obtained from these curves as shown in Table 3. The average energy absorption capacity values were found approximately for the RC beams without steel fiber and with steel fiber in dosage of 30 kg/m³ and 60 kg/m³ as 10557 kN.mm, 28076 kN.mm and 29828 kN.mm, respectively. When energy absorption capacity of the RC beams with steel fiber was proportioned to energy absorption capacity of the RC beams without steel fiber, it was observed that ductility of the RC beams with steel fiber in dosage of 30 kg/m³ and 60 kg/m³ was 2.66 and 2.83 times of that of the RC beams without steel fiber, respectively. A 100% increase in steel fiber dosage could increase the energy absorption capacity only 7%.

Amount of explosives used in the blast loading were 2.78 kg and 4.17 kg per cubic meter of the concrete. It was observed that in blast loading made by using Anfo in dosage of 2.78 kg/m³, the RC beams without steel fiber and with steel fiber in dosage of 30 kg/m³ and 60 kg/m³ were damaged heavily, but falling apart was less in the RC beams without steel fiber. In blast loading made by using Anfo in dosage of 4.17 kg/m³, all the beam series broke down completely at the mid-point. For this reason, contribution of steel fiber could not be observed for the Anfo dosage of 4.17 kg/m³.

Also, large shear cracks were observed at the supports of the RC beams without steel fiber for the explosive dosages of 2.78 kg/m³ and 4.17 kg/m³. However, for the RC beams with steel fiber, it was observed that damage occurred only at the mid-point where the explosive was placed and there were no cracks at the supports.

The reason for having considerable damage on the concretes with steel fibers is attributed to excessive amount of explosive material calculated by the Hauser expression. Therefore, it was proposed that either the amount of the explosive material defined by the expression should be reduced according to the test results, or the size of beams specimen should be increased, or the load carrying capacity should be increased to reduce the effect of blast.

Choosing the lower level concrete class in the explosive loading tests of RC beams is increased the level of damage. The chosen amounts of the dosage of

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Table 2— Mechanical properties of cylinder concrete sample

<table>
<thead>
<tr>
<th>Test sample</th>
<th>Dosage of steel fiber (kg/m³)</th>
<th>Average concrete compressive strength (N/mm²)</th>
<th>Decrease in concrete strength (%)</th>
<th>Modulus of elasticity (N/mm²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>No SFs</td>
<td>0</td>
<td>614.50</td>
<td>---</td>
<td>32950</td>
</tr>
<tr>
<td>SFC-30</td>
<td>30</td>
<td>545.40</td>
<td>12.66</td>
<td>32200</td>
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<tr>
<td>SFC-60</td>
<td>60</td>
<td>533.80</td>
<td>15.12</td>
<td>32050</td>
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</tbody>
</table>

Table 3—Test results of reinforced concrete beams

<table>
<thead>
<tr>
<th>Test element</th>
<th>Tensile, compression and stirrups steel</th>
<th>Theoretical failure load (kN)</th>
<th>First crack load (kN)</th>
<th>Experimental failure load (kN)</th>
<th>Experimental load/theoretical load</th>
<th>Toughness (kN mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SFRC 1-0</td>
<td>2Φ16</td>
<td>2016</td>
<td>110.00</td>
<td>262.30</td>
<td>1.48</td>
<td>10782</td>
</tr>
<tr>
<td>SFRC 2-0</td>
<td>2Φ10</td>
<td>176.40</td>
<td>112.40</td>
<td>260.15</td>
<td>1.47</td>
<td>9925</td>
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<tr>
<td>SFRC 3-0</td>
<td>Ø8/100</td>
<td>106.70</td>
<td>106.70</td>
<td>250.90</td>
<td>1.42</td>
<td>10965</td>
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<tr>
<td>SFRC 4-30</td>
<td>2Φ16</td>
<td>122.50</td>
<td>122.50</td>
<td>320.25</td>
<td>1.81</td>
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<tr>
<td>SFRC 5-30</td>
<td>2Φ10</td>
<td>176.40</td>
<td>118.90</td>
<td>330.00</td>
<td>1.87</td>
<td>27989</td>
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<tr>
<td>SFRC 6-30</td>
<td>Ø8/100</td>
<td>119.30</td>
<td>119.30</td>
<td>357.20</td>
<td>2.02</td>
<td>29856</td>
</tr>
<tr>
<td>SFRC 7-60</td>
<td>2Φ16</td>
<td>143.10</td>
<td>143.10</td>
<td>370.45</td>
<td>2.10</td>
<td>29979</td>
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<tr>
<td>SFRC 8-60</td>
<td>2Φ10</td>
<td>176.40</td>
<td>141.90</td>
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<td>2.09</td>
<td>30045</td>
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<tr>
<td>SFRC 9-60</td>
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<td>144.00</td>
<td>144.00</td>
<td>352.95</td>
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<td>29460</td>
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steel fiber were found to be insufficient to strengthen the RC beams to explosive loading.

**Revision of Hauser Expression**

The levels of damage observed in RC beams were shown in Figs 5 and 6. According to Hauser equation, the amount of explosive should be 1000 g for the test beams. However, it was observed that the RC beam became unusable and plastic joint was formed when the amount of explosive was decreased to 75% and 50% of the amount calculated by Hauser equation. Therefore, a revision was recommended for Hauser equation in the calculation of amount of explosive for surface blast loading. Hauser equation should be multiplied by a $\alpha$ coefficient, as shown in Eq (2). This $\alpha$ coefficient should be equal to 0.5 for all the test beams in this study since heavy damage was obtained when 50% of amount of explosive calculated by Hauser equation was used.

$$L = \alpha W^3 C D \quad \ldots (2)$$

In addition, the strength of concrete was not taken into account in Hauser equation to calculate the amount of explosives for the surface blast loading. The suggested $\alpha$ coefficient shall be increased or decreased in accordance with the strength of concrete and dosage of steel fiber.

**Conclusions**

An experimental study was performed on the RC beams with or without steel fibers in two dosages under the blast loading. Based on the test results, the following conclusions may be drawn;

(i) In RC beams with steel fibers, as the dosage of steel fibers increased, cracking and spalling of the concrete decreased. The random distribution of steel fibers inside concrete causes a decrease in the strength of the concrete.

(ii) Longitudinal reinforcement in RC beams yielded under blast loading. Steel fiber dosage of 30 kg/m$^3$ and 60 kg/m$^3$ was inadequate in preventing the damage in RC beams. Therefore, the size of RC beams specimen should be increased, or the load carrying capacity should be increased to reduce the effect of blast for the amount of Anfo used in the experiments.

(iii) Increase in steel fiber dosage could not prevent the heavy damage in RC beams. Only shear cracks in the support regions was prevented by addition of steel fiber in dosage of 30 kg/m$^3$ and 60 kg/m$^3$, as shown in Fig. 6. This shows that steel fiber was effective in blast loading. RC beams will be damaged less in blast loading when the steel fiber dosage was increased.

(iv) The effect of concrete strength and addition of steel fiber should be taken into the account when determining the amount of explosive by Hauser equation.

Choosing the lower level concrete class in the explosive loading tests of RC beams is increased the level of damage. The chosen amounts of the dosage of steel fiber were found to be insufficient to strengthen the RC beams to explosive loading. As a result, high strength concrete with high dosage steel fibers in the explosive loading tests of RC beams may be preferred.

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**References**