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ORIGINAL ARTICLE

Investigation of low-velocity impact behavior of two-way RC slab strengthening with basalt TRM strips

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Abstract
Reinforced concrete (RC) structural members could be subjected to impulsive impact loads due to various effects such as the collision of masses driven by rockfall, flood, landslide, avalanche, the crash of vehicles to structural elements in highway and seaway, airplane landing contact, the acting of explosion-induced air shock waves on structural elements as impulsive loads. The conventional design of RC slabs and similar structural members is carried out regarding vertical static and lateral dynamic loads such as earthquake and wind effects. However, the design phase mostly ignores impulsive loads such as impact and blast. Thus, these effects pose risks that the structures experience heavy damage or total collapse. Strengthening RC slabs with textile strips has become a preferred strengthening technique to prevent the collapse of structures and limit damage to structural elements. This study strengthened RC slabs with basalt textile reinforced mortar (TRM) strips in different widths, and layout patterns were tested for low-velocity impact load. In addition, the effects of BFRP fan-type anchors near the impact point on the behavior have also been investigated. The effect of various applied strengthening patterns on impact load transferred to specimens, dynamic responses such as acceleration, displacement, maximum strain, and dynamic failure modes occurred were investigated and interpreted in detail. The experimental results have also been compared with the improved finite element model (FEM) generated. It is demonstrated that the present FEM can be used to evaluate the impact response of the RC slabs with TRM strips.

Keywords RC slab · Impact load · Basalt TRM · Strengthening · Finite element analysis

1 Introduction

Reinforced concrete (RC) slabs generate usage areas in the structures, transmit dead and live loads to beam, column, and shear walls, and distribute lateral loads such as earthquake and wind effects to columns and shear walls. The traditional RC slab design includes considering these static and dynamic loads. However, the RC slabs may be exposed to impulsive loads such as impact and blast. Most rare impulsive loads could lead to severe damage and total collapse. Literature review unveils impact load as one of the structural members' most frequent impulsive load. [36]. As static loading differs, impact loading constitutes the inertia and strain-rate effects. Mechanical properties and stress–strain behaviors of materials are affected and changed by loading rate. The fact that the loading rate in monotonic static loading is much slower than in sudden dynamic impact loading causes the material behavior to change. This effect is defined as the strain rate effect. At the same time, dynamic impact loading causes a rapid and

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sudden movement in structural systems, causing an inertia force to occur in the opposite direction of the loading. Besides, although the impact loads act on structural elements quickly, they pose great risks of remarkable damage to structural members or even leading to the entire collapse of structures. Furthermore, for proper evaluation of impulsive load effects in numerical analysis, strain-rate dependent material properties and improver algorithm including bond-slip effect, erosion parameters should be considered [12]. The characteristics of the strain-rate-dependent material and the strain-rate-dependent contact behavior between materials are not fully known, and studies on these subjects are ongoing. It has become necessary to understand the impact load performance and impact resistance of structures, especially strategically important for civil or military structures, to ensure the safety of structures with inadequate impact resistance by strengthening. All these necessities have led to an increase in studies examining the behavior of structural systems or members under the effect of impact loads [34].

It was seen from the literature review that composite materials are preferred because of their advantages in strengthening the RC structural members against dynamic impulsive loads. In their study, Anil and Yilmaz [4] examined the effects of the method of strengthening reinforced concrete beams with insufficient shear strength with CFRP strips on the behavior under impact loading. In their study, Mercimek et al. [25] conducted comprehensive research including experimental and numerical analysis examining the behavior of reinforced concrete columns reinforced with CFRP strips under impact loading. The advantages of choosing composite materials in strengthening applications are that they can be easily applied to all kinds of structural elements because they are light, have high mechanical strength, are highly resistant to external factors such as corrosion and moisture, do not change the architectural dimensions of the structural elements on which they are applied because they are very thin, and are easy to apply and require little workmanship. As related to the RC slabs, the parameters that are effective on impact response, such as the rebar ratio [37] and placement inclination [35], grade of concrete [27], slab thickness [41], prestress [19] and post-tensioned applications [3], support conditions [39], voids existing in the slab, the contribution of steel fiber [29], the strengthening with Carbon [38], Glass, and Basalt Fiber Reinforced Polymer [40] has been previously investigated in the literature. Beckmann et al. [7] also investigated the impact behavior of high-performance (HP) and ultra-high performance (UHP) concrete. The dynamic responses of the fiber-reinforced self-compacting concrete plates subjected to impact load were examined by Kantar et al. [20]. Furthermore, there are comprehensive numerical studies related to the impact behavior of the slabs in the literature [28].

Fiber-reinforced polymer (FRP) fabrics manufactured using different materials have been preferred in strengthening applications because they can be applied to any surface and geometry without changing the dimensions and weight of the structural members because of their low thickness and weight. However, bonding the FRP material to the structural member with epoxy, an inorganic chemical material, makes such applications harmful to the environment. In addition, epoxy material has disadvantages such as losing its strength to the effects of fire and high temperature and impermeable to water vapor. It can also be applied in just a specific range of humidity levels. It has been observed that epoxy material is not permeable to water vapor, causing condensation and water accumulation on the surface it is applied to and causing moisture in the structures where it is applied, causing mold mildew and usage problems in the long term. When the disadvantages of FRP composite materials are evaluated, the strengthening technique with TRM elements has been developed and started to be used in strengthening applications to avoid these problems [24]. The literature review reveals that in the studies where the effects of the strengthening technique with TRM strips on the behavior of RC structural members are investigated, experiments are mostly carried out under monotonic static, quasi-static, and reversible repeated loadings [26]. However, studies focusing on the impact behavior of RC structural members strengthened with TRM strips are quite rare [6]. In the TRM strengthening technique, unlike the FRP fabrics technique, the composite textile is knitted in a mesh to reduce the cost. Besides, the mesh geometry is designed to place textile mesh into the mortar layer and increase adherence. In this technique, the textile mesh material adheres to the structural element to be strengthened, utilizing mortar [13].

Furthermore, placing the textile mesh layer into the mortar layer enables the strengthening technique to be applied on the surfaces with any humidity rate to protect against high heat and fire [14]. The strengthening technique using TRM strips is developed to eliminate the disadvantages of the strengthening technique applied by bonding the FRP to the surface with epoxy [11]. Interface material models between composite materials and adhesion surfaces are extremely important in evaluating the performance increase and positive effects of the strengthening detail applied in the strengthening techniques developed with composite materials on the structural element and for the numerical analysis models to provide compatible results that can coincide with the experimental findings in subsequent numerical analysis studies. The determination of the bond behavior between TRM and concrete is one of the important issues that should be known to calculate the general load–displacement behavior of RC structural members strengthened by TRM strips, to calculate the increase in their capacities and to determine the effects of the applied strengthening method

on performance [5]. However, in the comprehensive review, no research examined the bonding behavior between TRM and the concrete under the effect of impact load. It has been observed that the studies in the literature focused on the bond behavior under the effect of static loading. As seen in the literature review, studies on the interface material model between composite materials and the adhesion surface were largely carried out for static loading, and the same situation was observed in strengthening studies. There are an extremely limited number of studies on how strengthening methods developed using TRM strips increase and improve the behavior and performance of RC slabs under impact loading [31]. It has been seen that the number of research and experimental data on this subject is extremely limited, and an experimental study was planned to contribute to the literature on this subject. In addition, in a limited number of studies, it was seen that the composite material used for strengthening was carbon-based. There are also a few studies in the literature examining slabs strengthened with CFRP strips [38] and carbon TRM strips [31] to improve the behavior of RC slabs under sudden dynamic impact loading. However, no research has been found in which TRM strips produced using basalt material were used to improve the performance of RC slabs under impact loading. In addition, basalt material was preferred in the study because it is more environmentally friendly and less environmentally harmful than carbon-based materials. For these reasons, an experimental study was planned to strengthen RC slabs using basalt TRM strips and examine their behavior under impact loading.

In light of the literature review performed in the present study, an experimental program is planned to understand how the strengthening technique using basalt TRM strips can successfully enhance the performance of the RC slabs subjected to impact load. The RC slab test specimens were tested under the effect of impact loading using a drop-weight test setup designed by the authors [36]. A textile mesh knitted using basalt fibers, which is more cost-effective and less environmentally harmful, is preferred. Basalt TRM strips' strengthening layout and widths were taken as experimental variables. In addition to these variables, the effects of the usage of BFRP fan-type anchors near the impact load application point on the performance of the strengthening technique have been investigated. The application of fan-type anchors in the strengthening methods developed to improve the performance of reinforced concrete slabs under impact loading was carried out for the first time in the study conducted by Yılmaz et al. [38], and the use of BFRP fan-type anchors together with basalt TRM strips was examined for the first time in this study. To examine the effects of experimental variables on the impact behavior and dynamic responses of the RC slabs strengthened with TRM strips, time histories of impact load, acceleration, displacement, and strain recorded during the test were interpreted and discussed. The failure modes were evaluated by observing damage patterns and cracks. Furthermore, the finite element model (FEM) has been established to investigate the impact resistance numerically, and dynamic responses of the RC slabs strengthened with TRM strips. After comparing the experimental and numerical results, the present FEM can be used for non-linear impact analysis of the RC slabs retrofitted with TRM strips.

As stated above, after a comprehensive literature review, it was seen that there are an extremely limited number of studies examining strengthening techniques developed using TRM strips to increase the performance of RC slabs under the influence of dynamic impact loading. In addition, in this limited number of studies, it was determined that TRM strips produced using carbon-based materials were used, and no study was found with TRM strips using basalt material, which is more economical and environmentally friendly. In addition, in this study, applying BFRP fan-type anchors to delay the peeling of TRM strips from the surface close to the impact zone is thought to be an innovative aspect of the study that contributes to the literature on this subject. An experimental study covering all innovative aspects was planned, and the obtained results were interpreted to investigate the successful performance of the strengthening technique developed to improve the behavior of RC slabs under impact loading.

2 Experimental study

2.1 Test specimens and materials

In the experimental program, Seventeen RC slabs were cast and tested under impact loading with the same input impact energy ($9.81 \times 1.5 \times 84 = 1.2361$ kJ) utilizing the drop-weight test setup. The RC slabs were in dimensions of $1000 \times 1000 \times 80$ mm. One specimen was designed as the reference specimen to which TRM strengthening was not implemented. The rest of the specimens were strengthened using TRM strips. Experimental variables investigated are strengthening layout and widths of basalt TRM strips and whether BFRP fan-type anchors are placed at the TRM strip intersections. The properties of the test specimens can be given in Table 1. The widths of basalt TRM strips used for retrofitting RC slab test specimens were chosen as 50 mm and 100 mm. TRM strips with widths of 50 mm and 100 mm were bonded to tensile surfaces of the RC slabs orthogonally and diagonally in both one and two directions. Test specimens with the same characteristics were produced in two series. BFRP fan-type anchors application was applied to the RC slabs in one of these test specimen series and the retrofitting with TRM strips. The strengthening details and

Table 1 Properties of specimens

Spec. #	Compressive strength of Concrete f_C (MPa)	Basalt TRM Strip width (mm)	Basalt TRM strip layout	Anchorage usage
1	45.3	Reference (without strengthening)		
2	42.1	50	Orthogonal unidirectional	No
3	41.8		Orthogonal double direction	
4	42.7		Diagonal unidirectional	
5	43.0		Diagonal double direction	
6	41.4	100	Orthogonal unidirectional	
7	41.9		Orthogonal double direction	
8	42.6		Diagonal unidirectional	
9	42.2		Diagonal double direction	
10	42.3	50	Orthogonal unidirectional	Yes
11	42.5		Orthogonal double direction	
12	43.8		Diagonal unidirectional	
13	44.0		Diagonal double direction	
14	43.7	100	Orthogonal unidirectional	
15	43.4		Orthogonal double direction	
16	42.9		Diagonal unidirectional	
17	43.1		Diagonal double direction	

geometric dimensions of the RC slab test specimens can be depicted in Fig. 1. The deformed steel rebars with a diameter of 6 mm were placed orthogonally in both directions on the tension surface of the test specimens with a spacing of 150 mm. The mechanical properties of steel rebars were determined through tensile tests at a load rate of 1.0 kN/s [1]. As a result of the tensile test performed with five samples, average yield strength, ultimate strength, and Young's modulus were determined as $f_y = 426$ MPa, $f_u = 595$ MPa, and $E_s = 208$ GPa, respectively. The standard deviation values of the mechanical properties obtained from the tests of the reinforcement's yield strength, ultimate strength, and elastic modulus values were calculated as 0.95 MPa, 1.2 MPa, and 0.56 GPa, respectively. Steel rebars were bought from the same supplier once to prevent diverse material characteristics.

The targeted concrete compressive strength was 45 MPa in the experimental program. During the casting of each RC slab, five samples were taken. The dimensions of the samples are $150 \times 150 \times 150$ mm. RC slabs and their samples were in the same cure conditions until impact test day. On test day, concrete compressive strength was determined with a load rate of 0.5 kN/s by testing five samples. Table 1 presents the average values of test results. It is found that the concrete compressive strength ranges between 41.4 MPa and 45.3 MPa. These values are quite close to the targeted value. The compressive strengths determined from five samples for each slab were quite parallel values with a minor standard deviation [2]. Two different aggregates with 3–7 mm and 7–15 mm diameters were used to produce the RC slab specimens. The aggregates used are stream material and natural; no crushed stone was used.

Basalt TRM mesh is preferred for the strengthening technique. Being environmentally friendly and cost-effective are the main reasons for its preference. The basalt TRM mesh used is a bidirectional mesh with 25×25 mm gaps, and mechanical and geometrical properties are the same in both directions. The properties of the mesh can be seen in Table 2. The values given in Table 2 of the basalt TRM mesh material used in the study were provided by the manufacturer, and these values are minimum values guaranteed by the manufacturer [32]. The strengthening layout and geometrical dimensions of the basalt TRM strips bonded to the tensile surface of test specimens were presented in Figs. 2 and 3 for the RC slabs with no BFRP fan-type anchorages and the RC slabs with BFRP fan-type anchorages, respectively. Mortar with high compressive, flexural, and surface adherence strength is used in the strengthening technique to connect the basalt TRM mesh and RC specimens. These mechanical properties can be seen in Table 2. The mechanical properties of the mortar used to adhere the Basalt TRM mesh material to the RC slab surface are provided in Table 2 by the manufacturer [33]. These values are minimum values guaranteed by the manufacturer. In the study, the mortar material used for adhering the TRM strips to the surface is a ready-made product of a manufacturer and was obtained from the market. The mortar material does not contain additives or ingredients that increase its adhesion to the surface. One of the parameters examined in this study is using BFRP fan-type anchors at the intersection of TRM strips

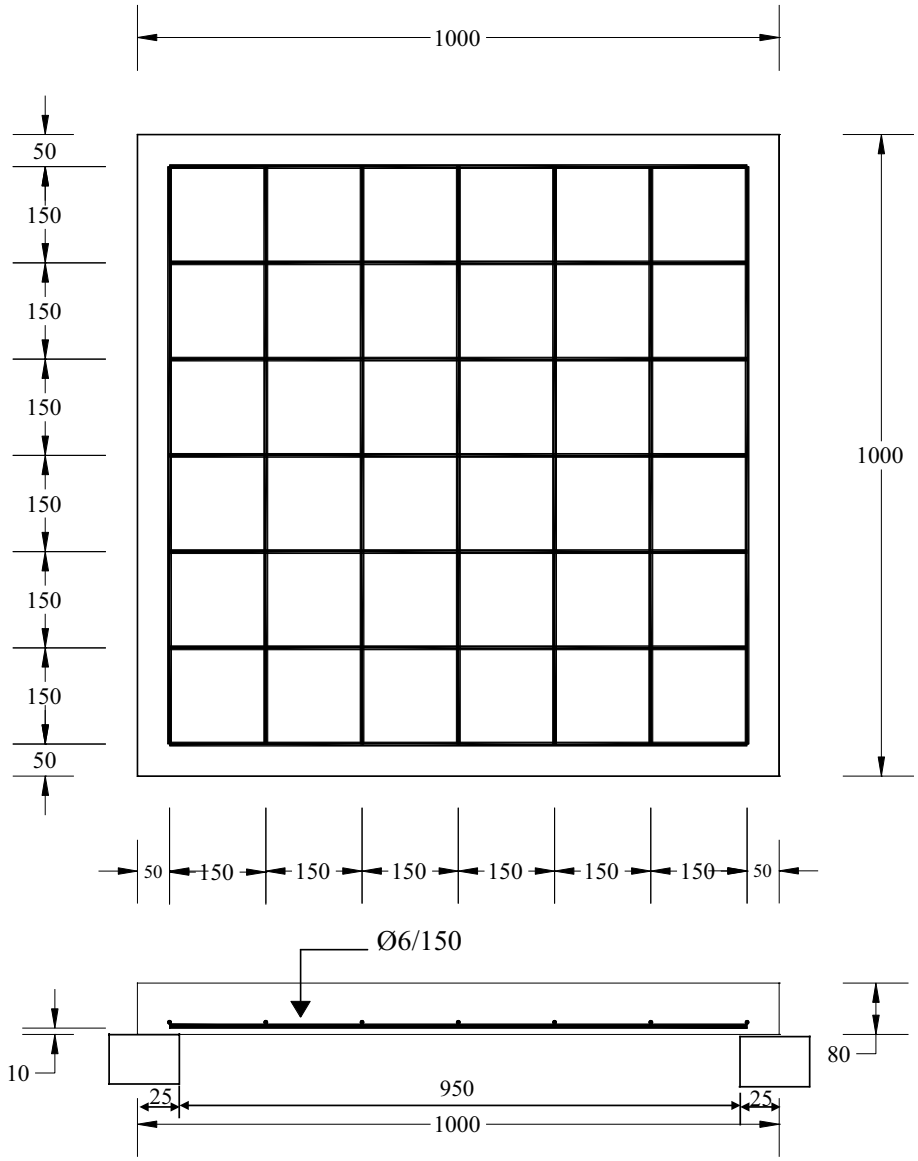


Fig. 1 Dimensions and reinforcement details of specimens (dimensions are mm.)

near the impact point. These anchors are also produced by knitting basalt fibers like the basalt TRM mesh used in this study. The mechanical properties of the anchors can be seen in Table 2 by the manufacturer, and these values are minimum values guaranteed by the manufacturer. Holes with a depth of 60 mm and a diameter of 10 mm are drilled to the locations where the intersection of the TRM strips will be present. After the drilling, holes are cleaned, then a 2-component anchor epoxy injection is applied. The properties of the epoxy can be seen in Table 2 by the manufacturer, and these values are minimum values guaranteed by the manufacturer. Then, basalt fiber anchors were placed in the holes, and the outer parts, called fan parts, were opened to form a circle with a diameter of 60 mm. The basalt fiber anchors were adhered to by injecting a two-component epoxy into the holes. The fan parts of anchorages have also adhered to the upper surface of the TRM strips with the epoxy. Figure 4 illustrates the steps of the applied strengthening method in the experimental program. The authors' previous study [31] can be examined for detailed descriptions of the process, including surface preparation, drilling anchorage holes, application of TRM strips and fan-type anchors, and curing.

2.2 Test setup and instrumentations

The drop-weight test setup designed by the authors for impact tests was used to apply impact loading. The setup is depicted in Fig. 5. In the setup, hammer weight could be varied from 84 kg to 250, while drop weight could be set up to 4 m to test various structural members. Many studies utilized this setup [37–39]. The RC slabs were subjected to the same input impact energy of 1.2361 kJ by a

Table 2 Mechanical properties of materials for strengthening

Remarks	Value
Basalt textile mesh	
Weight	350 g/m^2
Elastic modulus	85 Gpa
Tension strength	4000 MPa
Failure strain	2.1%
Mesh size	25 × 25 mm
Basalt fiber anchor	
Tension strength	> 2000 MPa
Elastic modulus	> 80 GPa
Failure strain	2.5%
Diameter	8 mm
Mortar	
Bending strength	> 10 MPa
Bonding strength	2 MPa
Compressive strength	60 MPa
Elastic modulus	> 20 GPa
Anchor epoxy	
Tensile strength	30 MPa
Elastic modulus	3800 MPa

hemispherical hammer weighing 84 kg and a drop height of 1500 mm. A high-strength steel plate, whose dimensions were 100 × 100 × 15 mm, was fixed at the center of the RC slab specimens to distribute the load.

RC slab test specimens were placed freely on steel support, and their corners were fixed with clamps. It can be considered that they have the hinge supported for four edges since vertical and horizontal translations are prohibited while rotations are free. The steel support frame, specially produced for the support of the specimens, was fixed to the RC floor of the laboratory with anchors and was prevented from rebounding or moving in the horizontal direction due to the impact loading applied. RC slab specimens were placed on the steel support so that 25 mm long sections in both directions remained on the support. The unsupported free openings of the slabs were 1000–2 × 25 = 950 mm (see Fig. 1) and placed on the steel support frame as a result of the impact loading applied due to the specific gravity of the specimens and the fixation of the steel frame to the laboratory floor, no rebound or horizontal movement occurred in the specimens or the steel support frame. Depending on hammer weight and drop height, the input impact energy level has been selected properly to observe impact-induced damage. Impact loads were measured with an ICP type-piezoelectric load cell connected to the hammer, and time histories of impact load were recorded. The impact-induced vibration responses of the slabs were measured with ICP-type piezoelectric accelerometers with a capacity of 5000 g. On the left and right sides of the impact load application point, with a distance of 150 mm, two accelerometers were fixed to slabs using a brass apparatus. This distance prevents accelerometers from damage due to the hammer during the drop. Four potentiometers were used for recording time histories of displacements. They are located at a 150 mm distance from accelerometers.

Furthermore, two strain measurements were taken for each direction from two points on TRM strips near the impact application point. A strain gauge was attached to four points in total on the basalt fiber strips embedded in the mortar, and then the strips were covered with mortar. Strain measurements were taken over the basalt fibers from which the basalt textile net was formed, and care was taken not to damage the strain gauge connection cables while covering the fibers with the mortar layer. The data logger system used for collecting impact load, acceleration, and displacement records is special for impact tests and allows a collection of 25,000 data per second simultaneously for these measurements [31].

3 Experimental results and discussions

In the experimental program, the time histories of the displacements, accelerations, and strains measured from RC slab test specimens and the impact loads transferred to test specimens were recorded under the impact loading. During tests, two acceleration-time measurements, four displacement–time measurements, and four strain–time measurements were taken from the RC slabs strengthened with TRM strips. Acceleration measurements were taken from two points, displacement from four points, and strain measurements from four points as close as possible to the impact point, symmetrically, on the RC slab specimens. Even though RC slabs are symmetrical elements and acceleration, displacement, and strain measurements are taken from equal distances to the symmetry axes, reinforced concrete is a non-homogeneous material. In addition, no matter how symmetrically the strengthening details applied to the RC slab specimens are arranged in a symmetrical geometry, all TRM strips can't adhere to the surface identically, and all plaster thicknesses are identical. Due to such differences, although the acceleration, displacement, and strain values measured from the left and right sides of the RC slabs are quite close to each other, they are not exactly the same. Among these values, the maximum measured values were selected, and the maximum acceleration, displacement, and strain values were used when interpreting the behavior of the specimens under the impact loading. The maximum time histories among these measurements for acceleration, displacement, and strain are presented in Figs. 6, 7, and 8, respectively. The graphs of change over time of the maximum acceleration, displacement, and strain values obtained

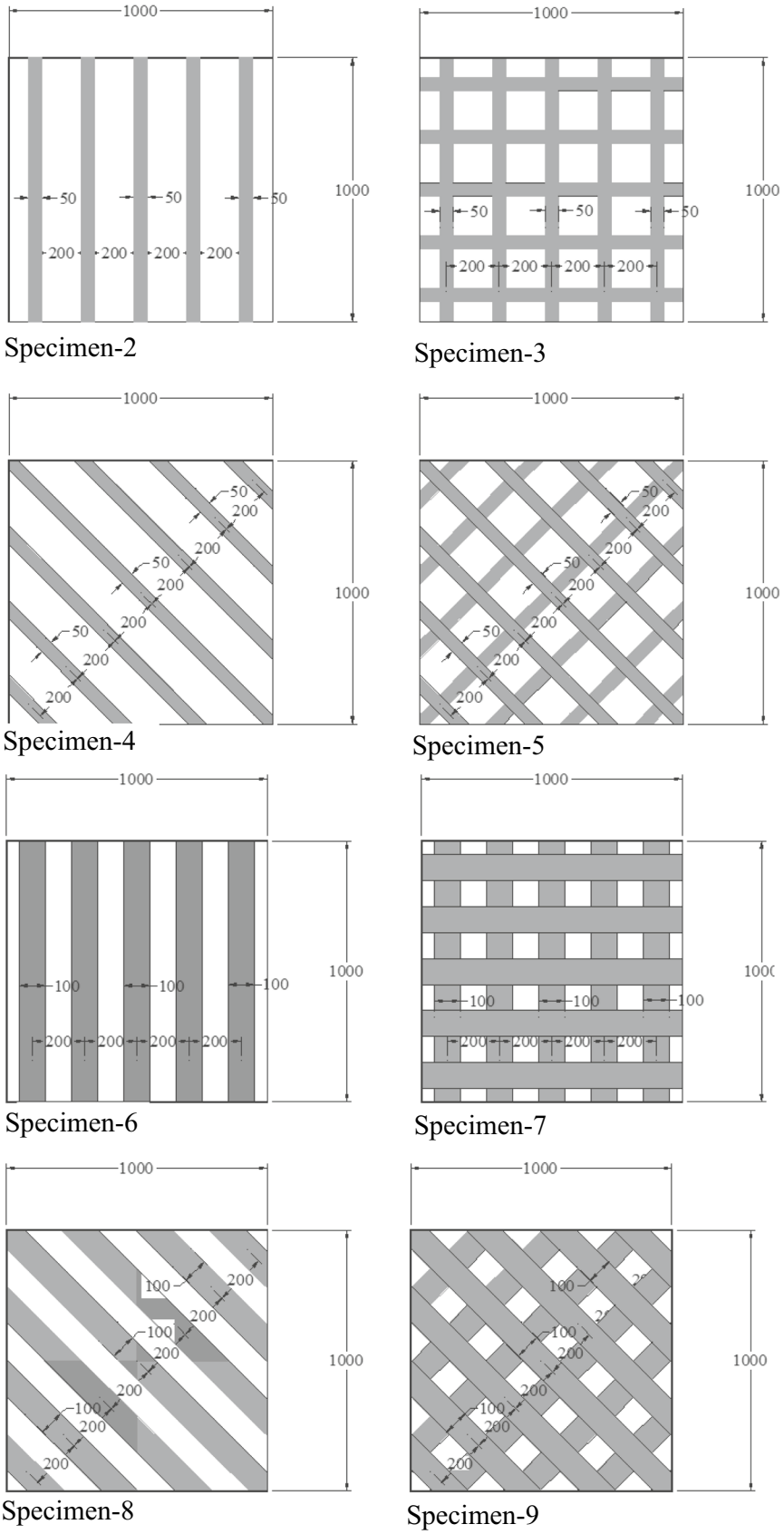


Fig. 2 Strengthening details of specimens without anchorages (dimensions are mm.)

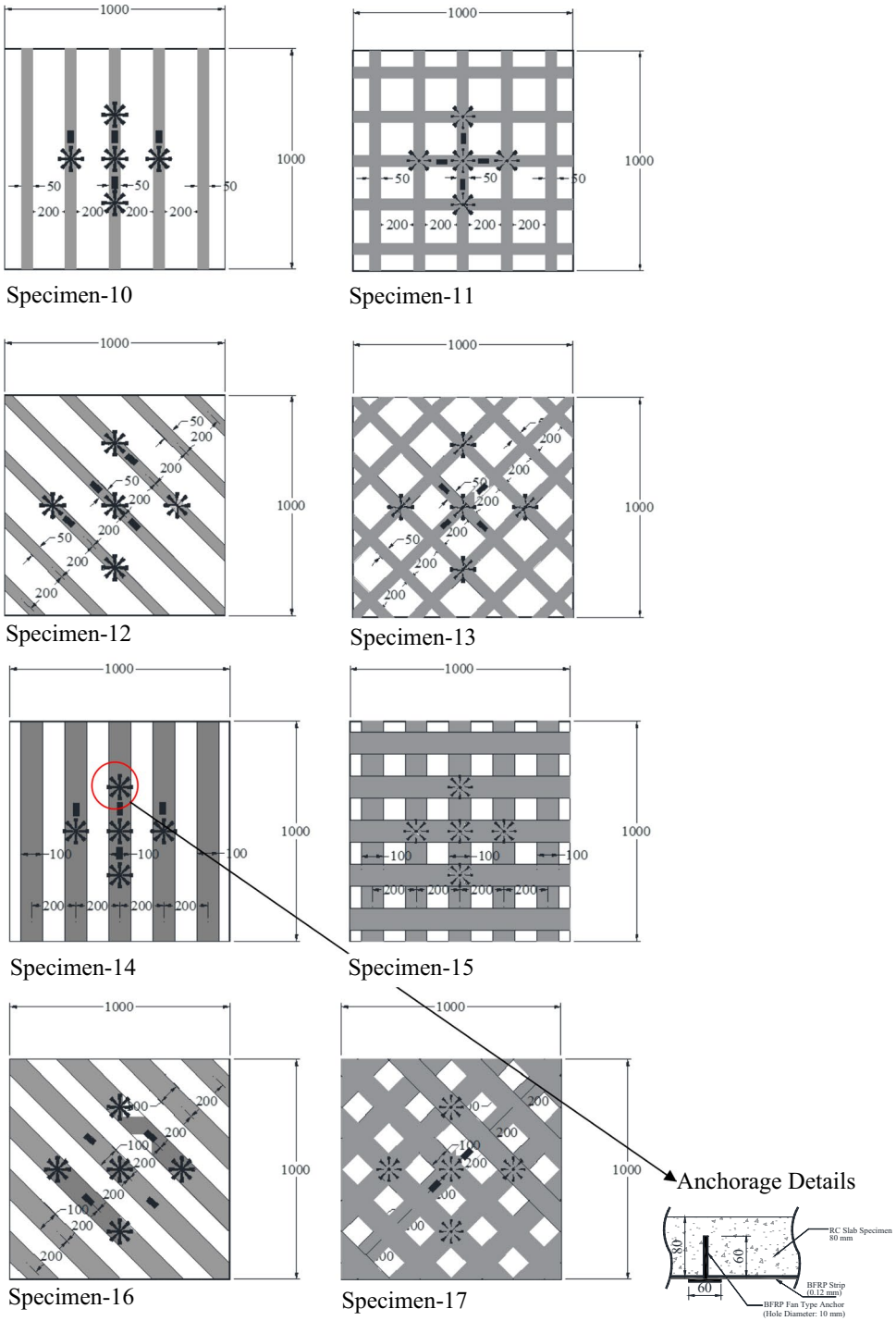


Fig. 3 Strengthening details of specimens with anchorages (dimensions are mm.)

from the sensor from which the maximum measurement was taken among these measurements are given in Figs. 6, 7, and 8. The time histories of impact loads transmitted to the RC slabs under input impact energy applied are presented in Fig. 9. The results obtained from the test conducted are given in Table 3. Figure 10 depicts damage distributions at tension surfaces of the RC slab specimens that occurred due to impact loading.

It has been found that the retrofitting method improved in the present study and applied to RC slabs significantly improves the impact resistance of the RC slabs and increases their performance. Compared to the reference specimen, Specimen-1, it is observed that the maximum left and right acceleration values of the strengthened specimens are greater by 101% and 101% on average, respectively. It is found that the maximum and residual displacement values of

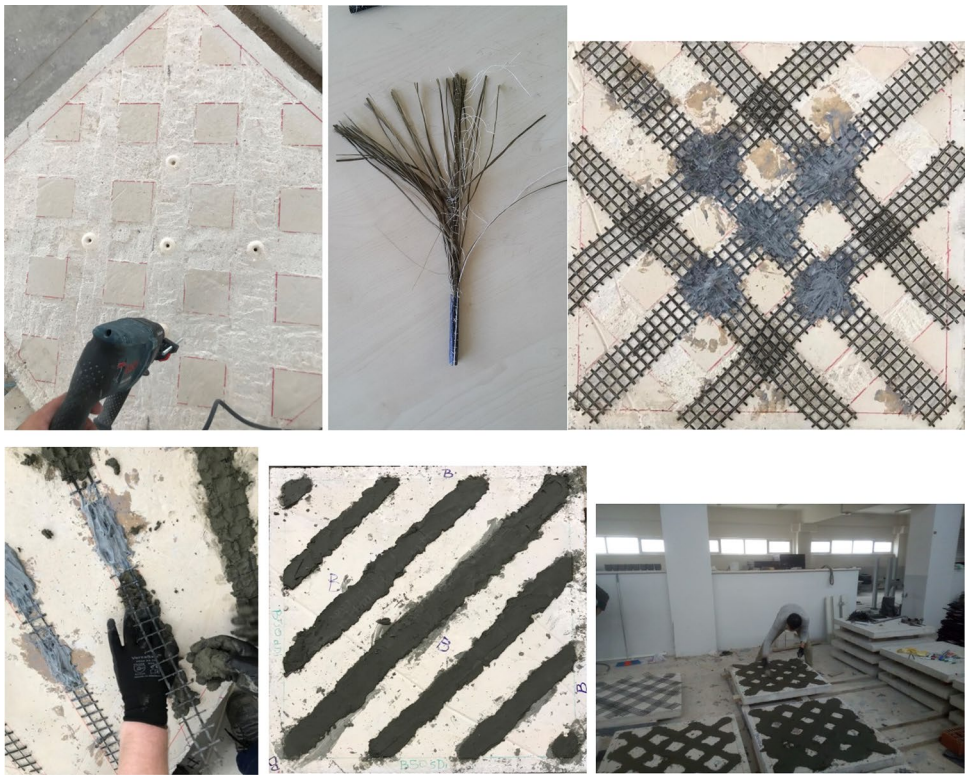


Fig. 4 Application steps of strengthening technique

the strengthened specimens are 157% and 306% less than the reference specimen on average, respectively. The strengthening technique has substantially increased acceleration values due to impact load by enhancing the stiffness and toughness of the RC slabs. Basalt TRM strips absorbed a large part of the input impact energy transferred to slabs with the effects of impact loading and, in this way, led to reduced displacement values that occurred on slabs. In addition to the decrease in displacement values, the strengthening with TRM strips significantly reduced the number and width of cracks occurring in slabs.

The width of the basalt TRM strips is one of the variables investigated in this study. This study used two different widths of 100 mm and 50 mm. The use of TRM strips with a width of 100 mm instead of 50 mm positively affected the behavior of RC slabs under impact loading. It has been found that both the left and right maximum acceleration values of the specimens retrofitted with 100 mm width strips are 17% higher than those retrofitted with 50 mm width strips. The increase in TRM strip width decreased the displacement values of RC slabs. The maximum and residual displacement values of the RC slabs with 100 mm width TRM strips are 40% and 73% less on average than those with 50 mm width strips, respectively. When the maximum strain values measured on TRM strips are examined, an increase in the width of TRM strips causes a significant decrease in the maximum strain values measured from TRM strips. This result from the experimental study demonstrates that under the effect of impact loading with constants input impact energy, TRM strips with a width of 50 mm were subjected to the more axial tensile force and took charge by far so that the RC slabs could absorb the applied impact energy. The maximum strain values of the specimens with basalt TRM with 100 mm width are 50% lower than those with 50 mm width TRM. This result is considered important proof that under the effect of applied impact loading with a constant energy level, the specimens strengthened using TRM strips with a width of 100 mm have much more residual strength and can resist impact loads with higher energy levels.

Another variable examined in the present study is that the strengthening with TRM strips has been applied in single or both directions. The placement of TRM strips in both directions for strengthening the RC slabs significantly positively affected the overall behavior and performance of the RC slabs under the effect of impact loading. On average, the left and right maximum acceleration values of the RC slabs strengthened in both directions are 31% higher than those strengthened in a single direction. The maximum and residual displacement values of the RC slabs strengthened in both directions are 49% and 123% less than those strengthened in a single direction, respectively. Maximum strain values of TRM strips bonded in both directions are 49% less than the TRM strips bonded in a single direction. These results showed that placing the TRM strips in both directions increases the maximum acceleration values while

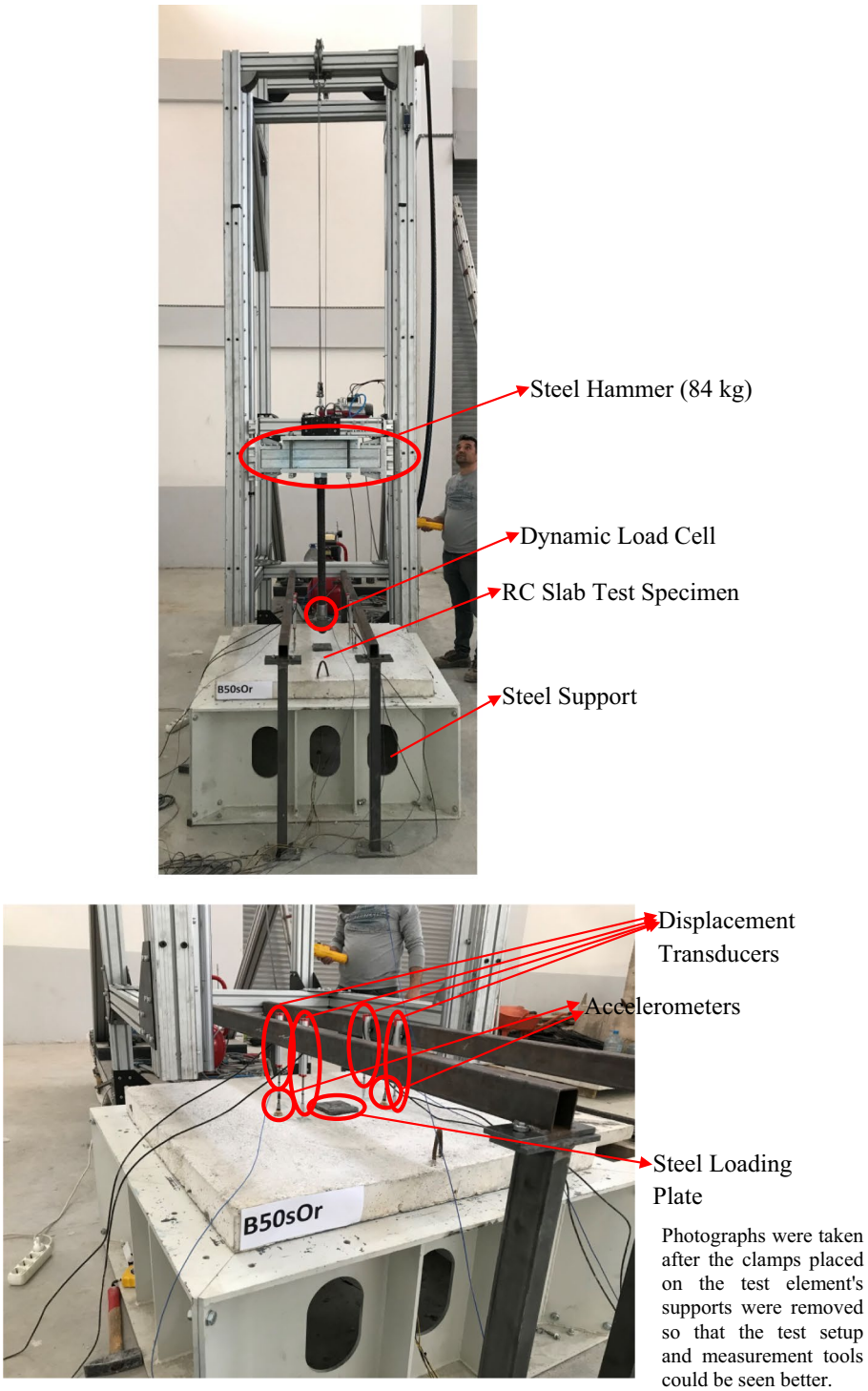


Fig. 5 Test setup and instrumentations

Photographs were taken after the clamps placed on the test element's supports were removed so that the test setup and measurement tools could be seen better.

significantly reducing the maximum displacement, residual displacement, and strain values.

Placing the TRM strips bonded to RC slabs orthogonally or diagonally is another variable examined in this study. It has been found from the experimental results that the diagonal strengthening layout with TRM strips has been more effective in enhancing the impact performance and resistance of the RC slabs than the orthogonal strengthening layout with TRM strips. It has been calculated that both the left and right maximum acceleration values of the specimens where the TRM strips are placed diagonally are 17% greater than those with an orthogonal layout. The maximum and residual displacement values of the test specimens with diagonal strips are 32% and 69% lower than those with orthogonal

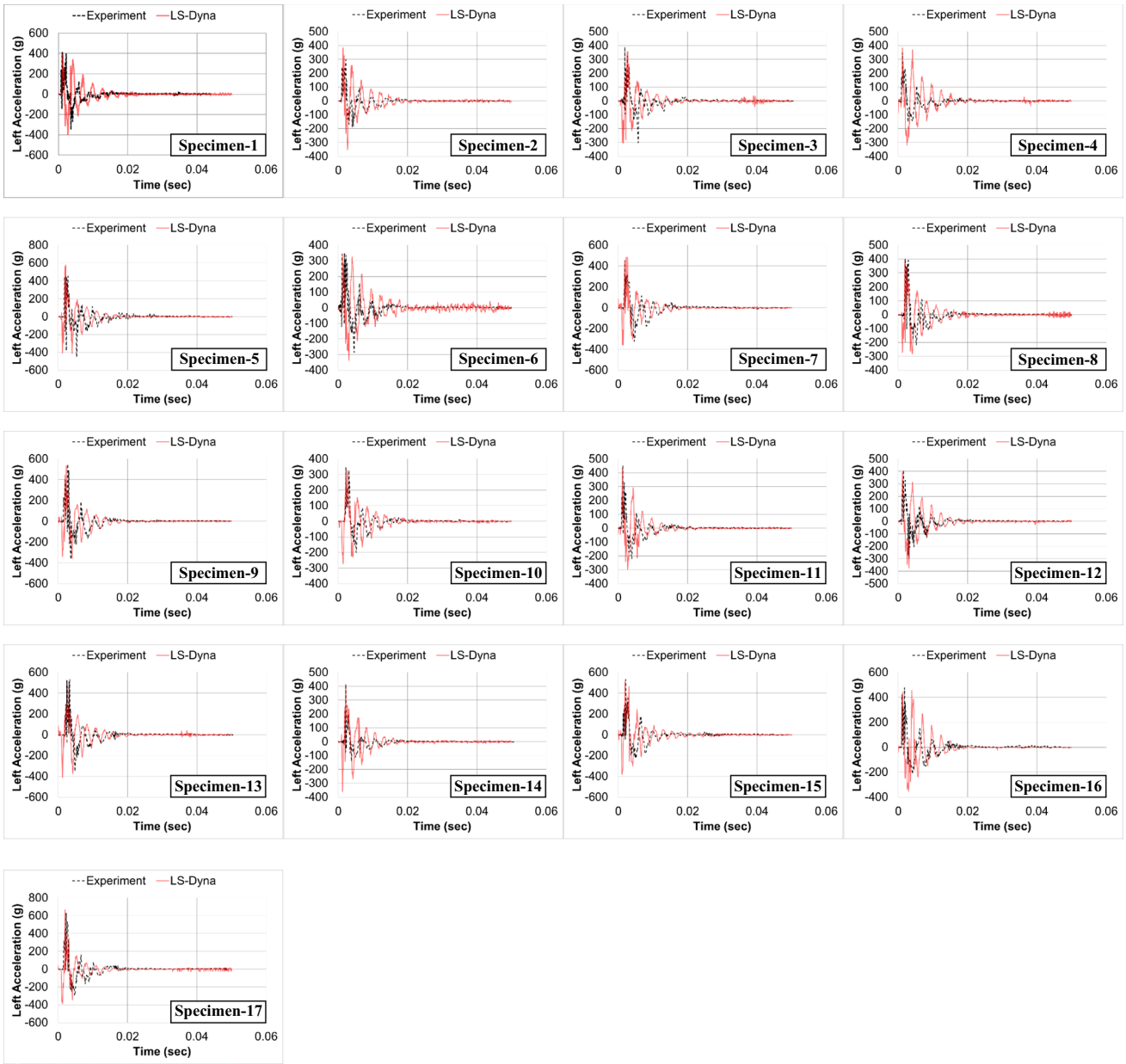


Fig. 6 Maximum acceleration-time graphs of specimens

strips. When the maximum values of strain measurements taken from basalt TRM strips are examined, it is observed that the maximum strain values from the test specimens with orthogonal strips are, on average, 74% higher than the test specimens with diagonal stripes. This result demonstrated that under the effect of impact loading with the same energy level, the orthogonal strengthening layout had to bear much more axial force for absorbing applied input impact energy than the diagonal layout. It is also concluded that under the effect of impact loading with the same energy level, the test specimens diagonally strengthened using TRM strips have much more residual strength and energy absorption capacity. They have succeeded in absorbing the resulting energy by reaching lower strain values.

Another variable investigated in the present study is whether BFRP fan-type anchors are applied at the TRM strip intersection regions near the point on which the impact load acts. The application of the BFRP fan-type anchors enhanced impact performance and resistance. Both maximum right and left acceleration values of RC slabs with anchorage are 18% higher than those of test specimens without anchorage. The maximum and residual displacement of the RC slabs with anchorage is, on average, 25% and 50% lower than those without anchorage. These results demonstrate that

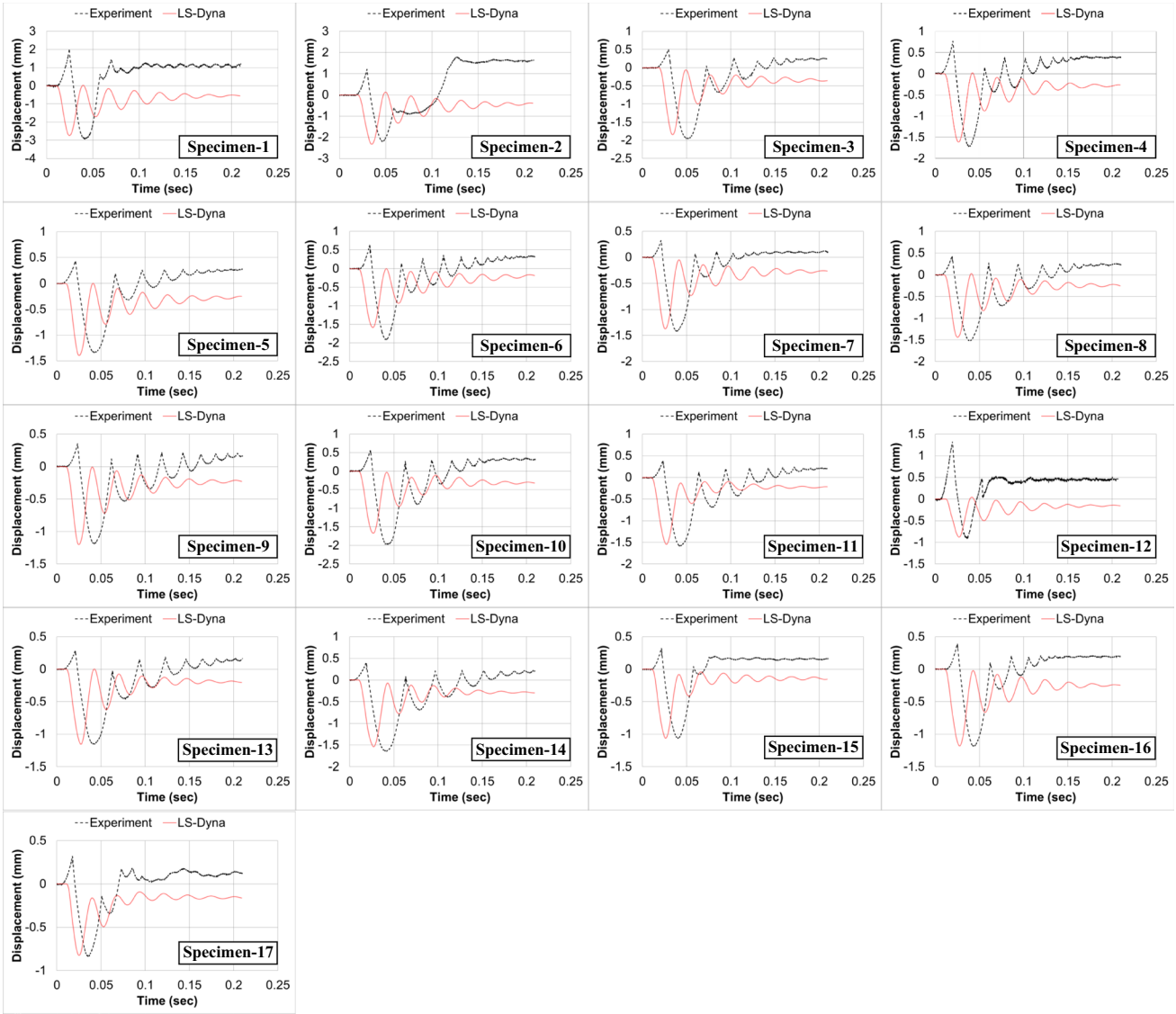


Fig. 7 Maximum displacement–time graphs of specimens

BFRP fan-type anchors placed at TRM strip intersections near the impact load application point delayed the debonding that will be able to occur between the TRM strips and the slab surface and have reduced the deformations due to the impact loading. When the maximum values of strain measurements taken on TRM strips with anchorage are examined, it is found that they are 12% higher on average than the strain values taken from TRM strips without anchorage. This result supports the finding that BFRP fan-type anchors improve the bonding between the basalt TRM strips and RC slabs. The fact that the maximum strain values of the strips with anchorage are higher than those without the anchorage demonstrates that the anchors have effectively absorbed impact load-induced energy. Experimental results indicate that impact loads change between 31.84 kN and 32.11 kN, while the average is 32.02 kN. These close values demonstrate the setup used can apply the impact loads with the same impact energies to slabs. When the effects of using BFRP fan-type anchors and other variables on the impact behavior of reinforced concrete slab test elements were examined, it was seen that the effect of using anchors on the maximum acceleration and maximum displacement values gave close results regardless of other variables. When the use of anchors is evaluated with the TRM strip change and TRM strip layout variables, the increase rates on the maximum acceleration values of the reinforced concrete slabs under the impact loading and the decrease rates on the maximum displacement values showed close ratios to each other. It was seen that they were not affected by other variables. However, when the residual plastic displacement

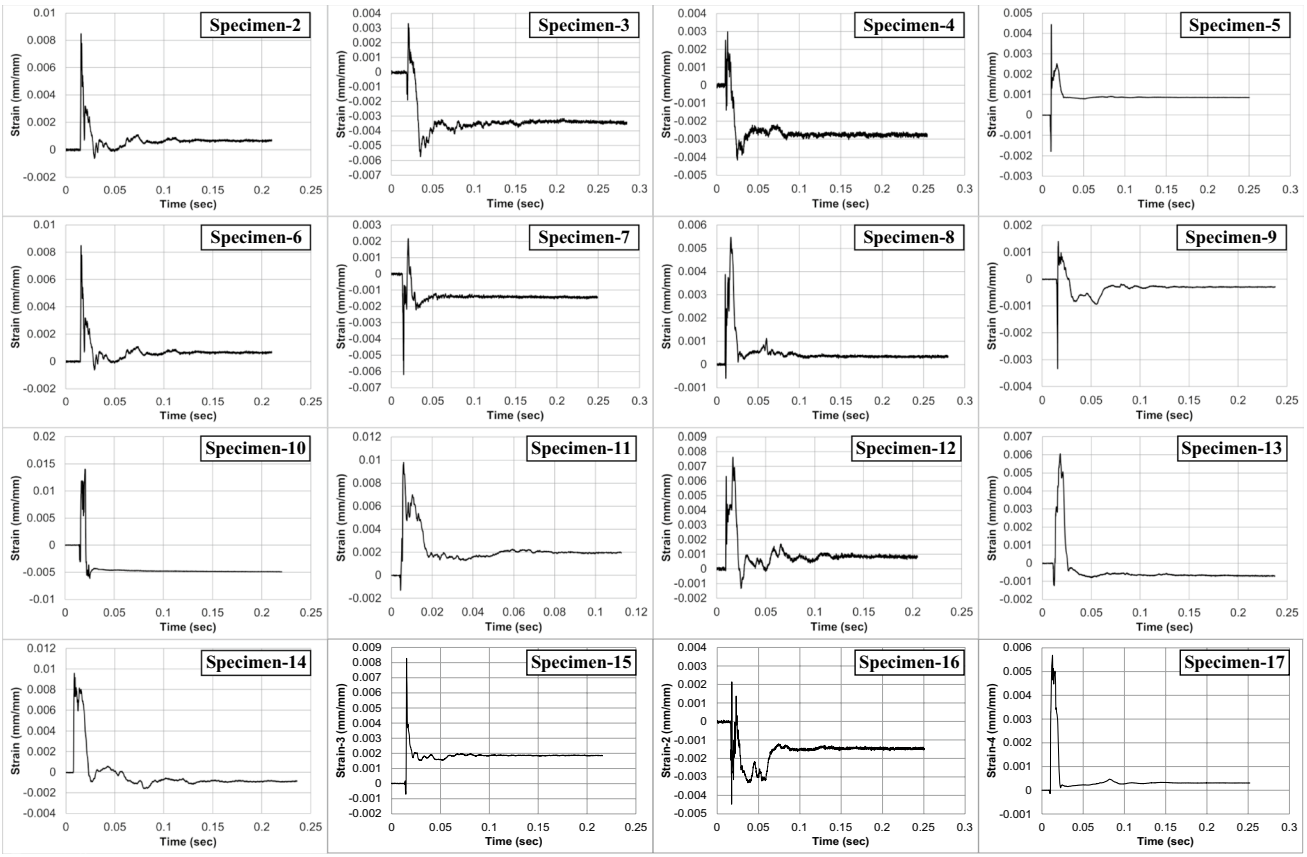


Fig. 8 Maximum strain–time graphs of specimens

values occurring in the specimens after the damping of the impact loading applied to the RC slabs were examined, it was seen that the other variables interacted with each other with the use of anchors and increased the positive effects of the use of anchors more. When the experimental results were examined, it was determined that the residual plastic displacement values in the RC slab specimens decreased with anchors. The reduction rate was affected by the TRM strip width and decreased more as the width increased. The use of anchors was more effective in specimens with a TRM strip width of 100 mm than in specimens with a TRM strip width of 50 mm. While the residual displacement values of 100 mm TRM strip width slabs with anchors showed an average of 74% less than those without anchors, the same reduction rate was calculated as 27% for specimens with 50 mm TRM strip width.

As well as dynamic responses such as maximum acceleration, displacement, and strain, the effects of the applied strengthening technique could also be observed from the waveform shape of impact-induced vibration characteristics of non-strengthening slabs. The TRM strengthening considerably increases test specimens' stiffness, toughness, and load-carrying capacity and contributes to accelerations that occur to be damped in a much shorter time. Besides, as can be seen from the waveform of acceleration time-histories, TRM strengthening positively affects the impact behavior of RC slabs by increasing amplitudes of accelerations in both directions, which are in the impact load direction and opposite direction. As a result of this bidirectional vibration movement, the energy transferred to specimens due to impact load has been absorbed more rapidly for RC slabs with TRM strips. The waveforms of the displacement time histories show that the maximum displacement of the non-strengthened Specimen-1 has increased rapidly, and most of the displacement remained on the specimen. Thus, Specimen-1 experienced more plastic residual deformation. However, for strengthened specimens, displacement responses increase up to maximum displacement at a slower rate than the non-strengthened specimen and decrease with the same ratio after peak value. Lower plastic residual deformations were observed in the slabs with TRM strips, and displacement of these slabs increased quickly and decreased at the same rate.

The experimental results reveal that diagonal strengthening has been more effective in improving the impact resistance of the slabs. With the effect of punching due to impact loading at the slab center, diagonal cracks occur by starting at the slab center and progressing toward corners

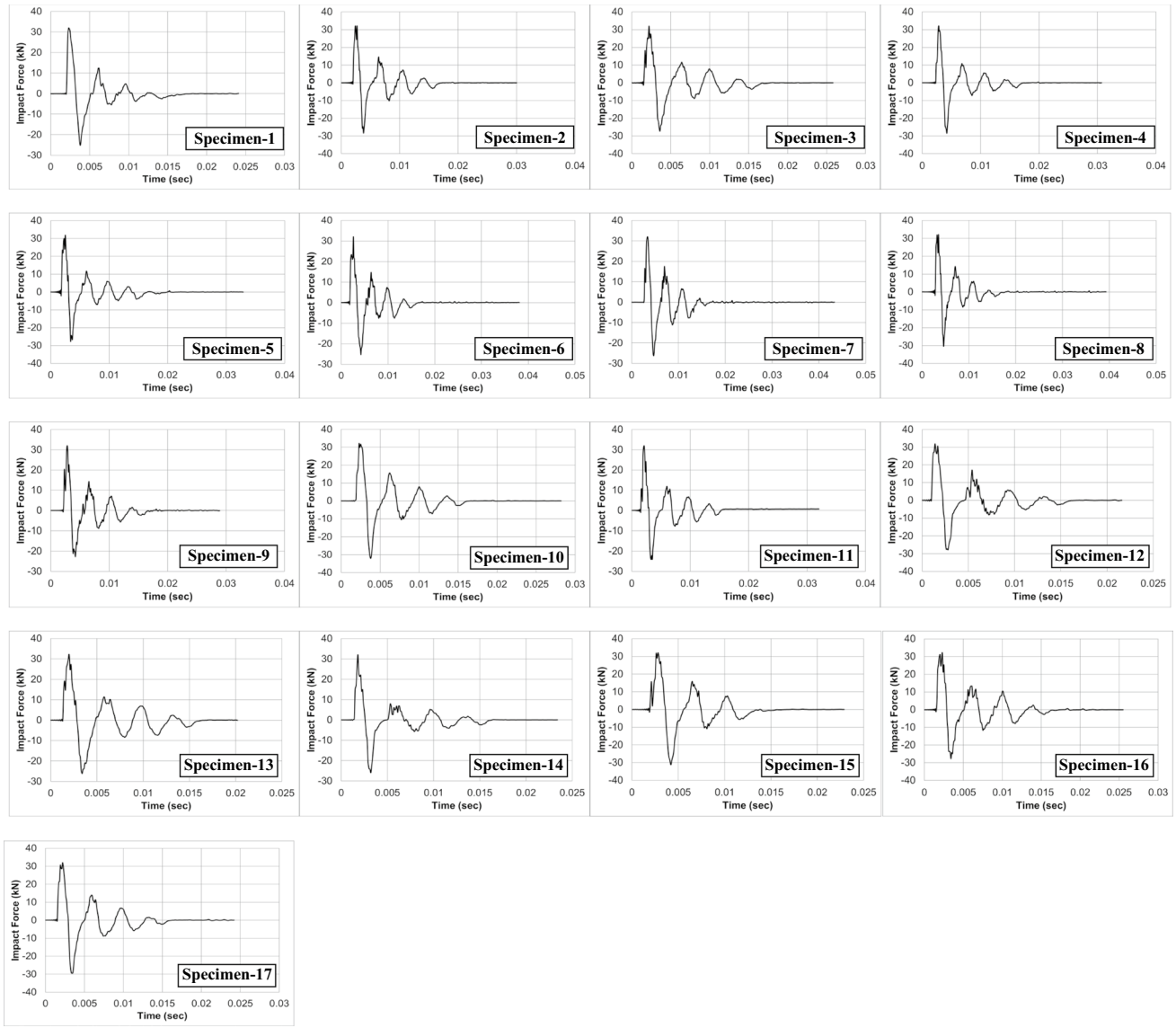


Fig. 9 Impact force–time graphs of specimens

(see Fig. 10). This observation for square test specimens is accordant the yield line theory [18]. It is explicit that diagonal cracks will be better limited when TRM strengthening is applied with a steeper angle against these cracks. Thus, placing TRM strips has exhibited better performance by limiting cracks and preventing greater displacement from occurring diagonally. Another variable examined in the study, apart from the TRM strip layout, is the width of the strips. The increase in the width of the TRM strips adhered to the RC slabs for strengthening caused a decrease in the number and width of cracks in the slabs. It was observed that the number and width of cracks in RC slab specimens retrofitted with 100 mm wide TRM strips were much less than those retrofitted with 50 mm wide TRM strips. In addition, another variable examined in the study is the anchor application, which is located in a region close to the impact load application point. It was observed that the number and width of cracks in the anchored specimens were much less than in the unanchored specimens. It is thought that the anchors increase the bonding of the TRM strips with the concrete and prevent cracks from passing through the lower parts of the strips. For these reasons, fewer and limited-width cracks occurred in the anchored specimens. It is thought that the increase in the width of the basalt TRM strips used for strengthening in RC slabs causes a decrease in the number and width of cracks that occur due to impact loading in the slabs, as the wider strips have larger adhesion areas and greater adherence to the surface, thus carrying more axial force and absorbing energy. Strips with larger widths reduce the number and width of tensile cracks that must occur in the concrete by

Table 3 Experimental results

Spec #	Left acceleration (g)		Right acceleration (g)		Displacement (mm)		Maximum strain (mm/mm)	Impact load (kN)
	Maximum	Minimum	Maximum	Minimum	Maximum	Residual		
1	219	− 172	217	− 96	4.93	1.12	–	32.0
2	298	− 186	297	− 127	3.99	0.89	0.0174	32.1
3	390	− 301	389	− 193	2.47	0.43	0.0097	32.0
4	348	− 152	347	− 308	2.76	0.51	0.0080	32.0
5	454	− 453	451	− 321	1.79	0.26	0.0062	31.8
6	348	− 283	345	− 229	2.57	0.61	0.0098	32.0
7	452	− 320	449	− 340	1.74	0.26	0.0085	32.1
8	400	− 219	399	− 241	1.97	0.39	0.0062	32.1
9	534	− 366	532	− 338	1.54	0.20	0.0055	32.0
10	346	− 201	345	− 152	3.22	0.78	0.0202	32.0
11	453	− 218	452	− 429	1.98	0.35	0.0111	32.0
12	410	− 293	407	− 223	2.23	0.47	0.0091	32.0
13	538	− 351	537	− 180	1.45	0.16	0.0073	32.1
14	414	− 144	412	− 319	2.07	0.41	0.0115	32.0
15	533	− 220	532	− 279	1.39	0.15	0.0090	32.0
16	472	− 214	469	− 196	1.58	0.20	0.0066	32.1
17	629	− 289	628	− 483	1.16	0.12	0.0058	32.0

absorbing the tensile stresses caused by the tensile force that the concrete must bear. Increasing strip width has resulted in much fewer unreinforced areas remaining on the lower surface of RC slabs where tensile stresses occur, and the limited number of cracks that occur have occurred in these small unreinforced areas.

Important results were obtained when the maximum displacement and permanent plastic displacement values under the impact load in RC slabs strengthened with Basalt TRM strips were examined in terms of the variables included in the experimental program. The diagonal placement of TRM strips adhered to the RC slabs for strengthening limited the displacement values much more than their orthogonal placement, and fewer displacement values were measured. Maximum displacement and permanent displacement values of RC slabs strengthened with diagonal strips showed much smaller values, on average, 32% and 69%, respectively, than the specimens strengthened with orthogonal strips. The maximum displacement and permanent displacement values of the specimens retrofitted with 100 mm wide TRM strips are, on average, 40% and 73% less, respectively, than those strengthened with 50 mm wide TRM strips. Another variable examined in the experimental study is the BFRP fan-type anchor application, where impact loading is applied on the slabs. Anchor application caused a decrease in the displacement values of the specimens, and the maximum displacement and permanent displacement values of the anchored RC slabs were 25% and 50% smaller on average, respectively, than the unanchored specimens. The changes in the specimens' maximum and permanent displacement values are presented in the graph in Fig. 11**.** When the values presented in Fig. 11 are examined, it is seen that the variables examined within the scope of the study on the maximum displacement values and residual displacement values have similar effects, and both displacement values show similar behavior trends.

In the same way, both displacement values are reduced to a greater extent when TRM strips are used in two directions than when they are used in one direction. TRM strips in the diagonal direction caused a greater decrease in both the maximum and residual displacement values compared to the orthogonal use. Using anchors in TRM strips caused a greater decrease in the maximum and residual displacement values than the specimens strengthened with unanchored strips.

It is thought that the method developed in the article will have very important contributions in practice and will provide benefits from many perspectives. The most important of these benefits is the economic contribution it will provide. When the studies in the literature are examined, it is seen that the approach of completely covering the entire structural element with a TRM layer is generally preferred in strengthening techniques using TRM. In the strengthening method proposed within the scope of this study, instead of covering the tensile surfaces of the slabs entirely with a TRM layer, it was preferred to apply strengthening with TRM strips in different patterns. Implementing the strengthening technique developed with strips will significantly reduce the material used in the planned strengthening method. The materials

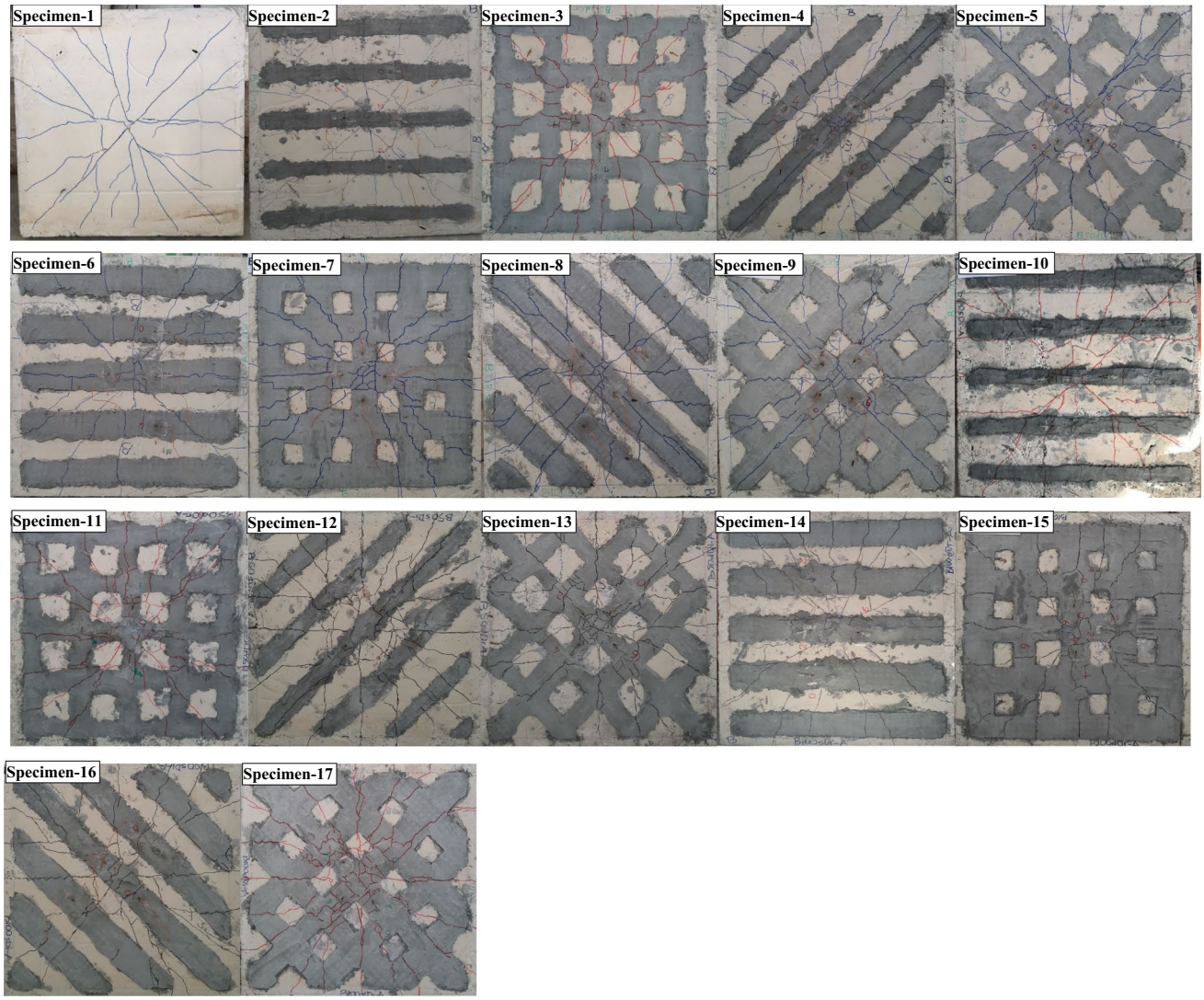
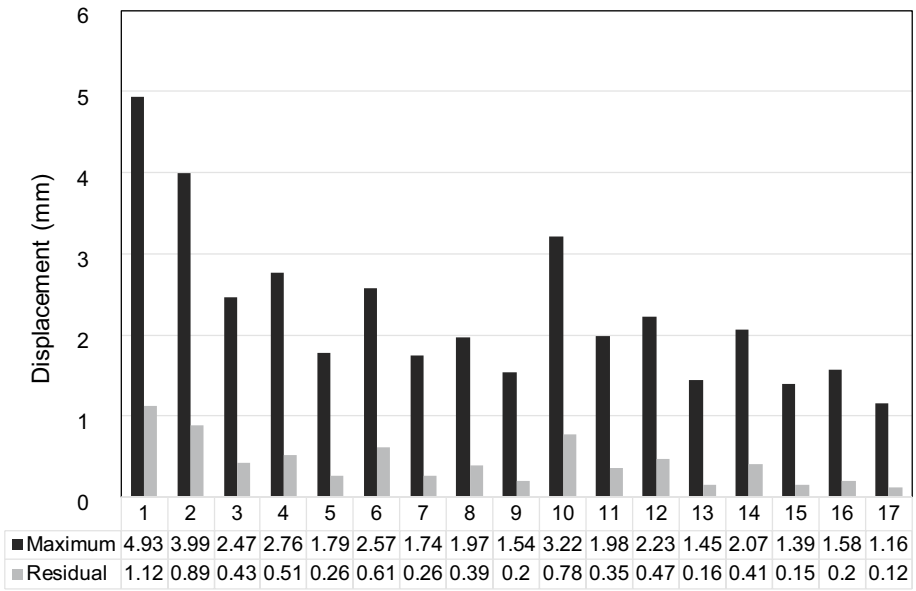


Fig. 10 Crack distribution of specimens after test

used in this study are quite expensive, as are the other composite materials' strengthening methods.

For this reason, it aims to reduce the cost and provide significant economic gain by reducing the materials used in the innovative strengthening technique using the strip proposed in the article. In addition, in the strengthening technique that has been developed, making the application in strips in much smaller areas instead of in a large area is an important factor that is highly effective on the workmanship and the success of the method to be applied. It is an application choice where it is much more difficult to adhere very large composite parts to large areas in real structures in applications made on the entire slab surface. It is possible to encounter problems that ultimately affect the application's success. In the strengthening techniques applied with composite materials, the success of the material's adhesion to the surface is a parameter that highly affects the success obtained from the strengthening method. Due to air gaps that may remain during the bonding of very large areas, the composite material cannot adhere to the surface in the desired smoothness and undulation. It is thought that sticking much smaller composite parts to the surface with strips will provide ease of workmanship and be effective in achieving success. It is believed that the innovative strengthening method presented in this article using strips will give more successful results because it is economical and easier to apply, reduces labor, eliminates some problems encountered during the application, and significantly contributes to the literature.

With the strips proposed in the study, the strengthening approach will gain much more from labor and application time. Adhesion of composite material in smaller areas is a much easier application method. Placing a single composite layer with a total size of slab area properly and ensuring that it adheres smoothly is a much more difficult and



	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
Maximum	4.93	3.99	2.47	2.76	1.79	2.57	1.74	1.97	1.54	3.22	1.98	2.23	1.45	2.07	1.39	1.58	1.16
Residual	1.12	0.89	0.43	0.51	0.26	0.61	0.26	0.39	0.2	0.78	0.35	0.47	0.16	0.41	0.15	0.2	0.12

Fig. 11 Change of displacement values of specimens

labor-intensive application than small strips. In real-life applications, the slabs are suspended above the applicator, and the application areas are much larger than the scaled specimens, making the alternative of strengthening coating with composite in the form of a single sheet inapplicable in some cases. However, the smaller strips recommended in this study, which are much easier to control and adhere to, will provide much greater convenience in terms of time and labor. As it is known, in the strengthening techniques applied with composite materials, the material is properly adhered to the surface without bending as much as possible without air gaps, which is the parameter that significantly affects the success of the applied strengthening.

For this reason, making the application in the form of smaller strips will prevent production errors that will adversely affect the performance of the strengthening method. To emphasize again, the advantages of the strengthening method developed using the strips suggested in the study over the strengthening method applied by covering the entire surface are not only that it is economical due to the use of less material and that it can be applied in a shorter time and with less labor. At the same time, the strengthening applied with the strip also eliminates these important risks that will affect the strengthening performance, as it is easier to adhere the strips to the strengthened structural element without any air gaps under it, without being undulation. The presence of these risks in the strengthening details applied by covering the entire surface with composite materials may cause a decrease in the performance that can be gained.

4 Numerical analysis

The FEM of the RC slabs with Basalt TRM strips exposed to impact loading was generated in software [21]. The finite element analysis (FEA) software has a wide spectrum of material models for modeling the dynamic behavior of concrete. It includes advanced contact algorithms for accurately reflecting the interaction of collided parts in the impact simulation. The FEA software could perform nonlinear dynamic analysis using the explicit solver, includes many concrete material models [31], and is commonly used for impact and blast analysis. [15].

The presented FEM consists of the RC slab, steel rebar, Basalt TRM strip, loading plate, and hammer parts. While an 8-node hexahedron solid element was used for modeling slab, plate, and hammer, the steel rebars and TRM strips were modeled with a Hughes-Liu beam and fully-integrated shell element [21], respectively [30]. Full adherence between concrete and rebar was defined with the CONSTRAINED_LARGRANGE_IN_SOLID algorithm [16]. After mesh convergence trials, it has been determined that the element sizes of 20 mm, 25 mm, 10 mm, and 5 mm for concrete, reinforcement, TRM strips, and hammer yield accurate results. Further refinement on mesh size has almost no effect on outcomes, although it increases solution time. Impact load was applied by defining the velocity of the hammer at the moment of collision. In the experimental setup used in the experimental study, the rails on which the falling weight moves are specially coated with chrome and have features that reduce friction

to a negligible level. For this reason, the friction in the dropped steel weight is neglected.

The concrete material was modeled using MAT_072R3 [17], considering a strain-rate effect, plasticity, and shear failure damage. The FE software takes unconfined concrete compressive strength from the user to build MAT_072R3. It computes other needed parameters. The compressive strength has been taken as 35 MPa for the MAT_072R3 since this value is cylinder compressive strength corresponding to the cubic compressive strength of 45 MPa in Eurocode 2 [8]. The erosion function [15], which removes damaged concrete from the solution and prevents computational overflow, has been added to MAT_072R3. The maximum principal strain belonging to concrete was taken as the erosion criterion, and it was assumed as 0.005 mm/mm with a trial-and-error approach performed [31]. The concrete density was defined as 2400 kg/m^3. The reinforcements are modeled using an elastic–plastic without the hardening material model in the numerical model. A linear elastic material model is used for TRM strips. The steel yield strength, elastic modulus, Poisson's ratio, and density were defined as 576 MPa, 200,000 MPa, 0.3, and 7850 kg/m^3. The Elastic Modulus, Poisson's ratio, and the density of TRM strips were 85,000 MPa, 0.45, and 2700 kg/m^3. The hammer and loading plate were rigid materials.

Impulsive loading increases steel and concrete materials' tensile and compression strength [12]. Many studies focused on the strain rate effect. They demonstrate that considering the strain rate effect in impulsive loading is compulsory for the accurate evaluation of dynamic responses [9]. The present FEM considers the strain rate effect by enhancing materials' tensile and compression strength with a Dynamic Increase Factor (DIF). DIF is a ratio of dynamic strength to static strength, and there are many equations related to DIF in the literature [23]. The tensile and compression DIFs for concrete material defined by Hao and Hao [17] were utilized in the present FEM. Besides, the DIF equations Malvar [22] presented were used for steel rebars. The compressive (CDIF) and tensile (TDIF) of the concrete material at the strain rate $\dot{\varepsilon}_d$ are given in Eqs. 1 and 2, respectively [12].

$$\mathrm{CDIF} = \frac{f_{cd}}{f_{cs}} = \begin{cases} 0.0419\left(\log\dot{\varepsilon}_d\right) + 1.2165 & \text{for } (\dot{\varepsilon}_d \le 30\ \mathrm{s}^{-1}) \\ 0.8988\left(\log\dot{\varepsilon}_d\right)^2 - 2.8255\left(\log\dot{\varepsilon}_d\right) + 3.4707 & \text{for } (\dot{\varepsilon}_d > 30\ \mathrm{s}^{-1}) \end{cases} \tag{1}$$

$$\mathrm{TDIF} = \frac{f_{td}}{f_{ts}} = \begin{cases} 0.26\left(\log\dot{\varepsilon}_d\right) + 2.06 & \text{for } (\dot{\varepsilon}_d \le 1\ \mathrm{s}^{-1}) \\ 2\left(\log\dot{\varepsilon}_d\right) + 2.06 & \text{for} (1\ \mathrm{s}^{-1} < \dot{\varepsilon}_d \le 2\ \mathrm{s}^{-1}) \\ 1.44331\left(\log\dot{\varepsilon}_d\right) + 2.2276 & \text{for } (2\ \mathrm{s}^{-1} < \dot{\varepsilon}_d \le 150\ \mathrm{s}^{-1}) \end{cases} \tag{2}$$

While f_{cd} and f_{td} are the dynamic compressive and tensile strengths at the stain rate $\dot{\varepsilon}_d$, f_{cs} and f_{ts} are static compressive and tensile strengths, respectively. Moreover, for a given strain rate $\dot{\varepsilon}$, the tensile and compressive DIFs of steel material could be determined via Eq. 3. The α coefficient can be calculated through f_y as follows:

$$\mathrm{DIF} = \left(\frac{\dot{\varepsilon}}{10^{-4}}\right)^{\alpha} \tag{3}$$

$$\alpha = 0.074 - \frac{0.04 f_y}{414} \tag{4}$$

The RC slabs were freely mounted on the steel support in the tests, and the horizontal and vertical translation movements were prevented with the clamps applied to the four corners region. Photographs were taken after the clamps placed on the test element's supports were removed so that the test setup and measurement tools could be seen better. The seating distance was 25 mm. Similarly, in the FEM, the translational degree of freedom (DOFs) of nodes in the edge area was constrained using the BOUNDARY_SPC_SET keyword [15]. The interface nodes of the RC slab and the loading plate were merged to get a fully bonded contact behavior. These two parts are fixed together in the test by anchored studs. The penalty-based contact algorithm was used to interface the hammer and the loading plate. The cohesive contact behavior between the bottom surface of the RC slabs and Basalt TRM strips was represented with a penalty-based tiebreak contact algorithm. The tiebreak contact uses stress- or force-based failure criteria [10]. Stress-based failure criterion was used for modeling bonding failure via Eq. 5:

$$\left(\frac{|\sigma_n|}{\mathrm{NFLS}}\right)^2 - \left(\frac{|\sigma_s|}{\mathrm{SFLS}}\right)^2 \ge 1 \tag{5}$$

where σ_n, σ_s are normal tensile and shear stress at the contact interface. The NFLS and SFLS refer to normal tensile failure and shear stress, respectively [10]. In the literature, the authors have not met advanced mathematical models verified with tests for the bond between RC slabs and Basalt TRM strips under the impact loading. Thus, the NFLS and SFLS were determined with trial and error. When these failure stress values were assumed as 10 MPa, it was found that numerical and experimental results converged. The tied contact function was utilized in the anchorage region to reflect full bonded behavior between concrete and TRM since it has not observed debonding in these areas during tests. Figure 12 depicts the FEM generated. The displacement and acceleration time histories were calculated via the present FEM. The equivalent plastic strain distribution

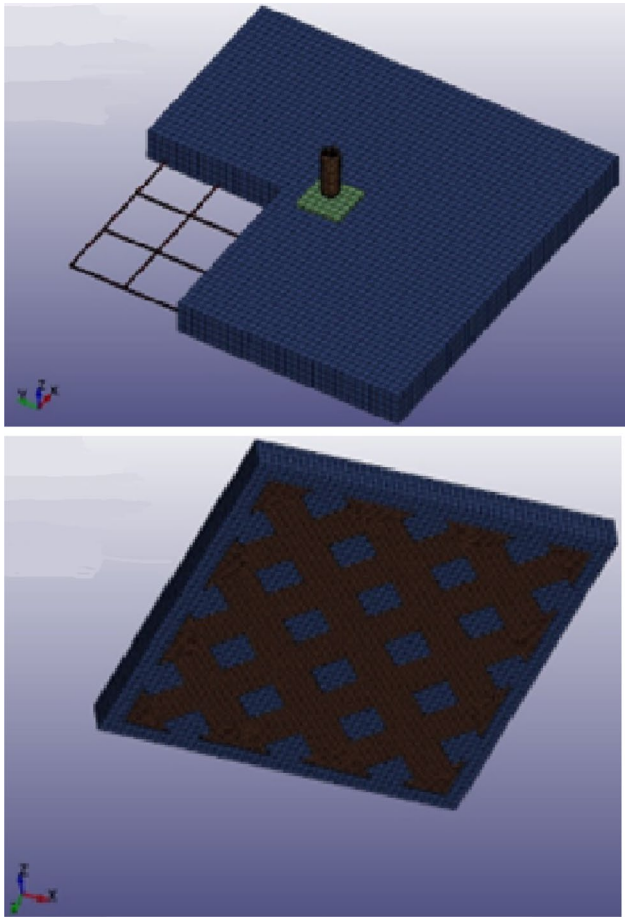


Fig. 12 The finite element model of the steel hammer, steel reinforcement, RC slab, and Basalt TRM strips

was also obtained and presented in Fig. 13. Numerical and experimental acceleration and displacement time histories are shown in Figs. 6 and 7. Table 4 also summarizes numerical and experimental results.

The comparison of experimental and numerical results shows that average differences are 6%, 4%, and 29% for maximum acceleration, displacement, and residual displacements. These differences mainly stem from the non-homogenous nature of concrete and the support conditions. In addition, the fact that the general material behavior changes as a result of the loading rate of the materials, in short, the strain-rate effect, is an important issue that affects the differences between the experimental and numerical analysis results. The numerical analysis study considered the strain rate effect for concrete, and the strain rate functions preferred in the literature were used. However, the strain rate effect for the TRM material in RC slabs and the mortar material used to connect this material to the surface could not be considered since there is no study on this subject in the literature. In addition, the literature has not found a generalizable strain-rate function for the interface bond stress-slip displacement material model between the TRM strips used for strengthening and the concrete surface. Failure to consider the strain-rate effect in these materials has been effective in the differences between experimental and numerical results, especially in RC slabs. The effects, such as environmental conditions, care, cure conditions, and compaction during the cast, lead concrete to lose its homogeneity. However, concrete is homogenous for whole sections in numerical models, and it is impossible to consider its non-homogeneous nature in the FEM exactly. Besides, support conditions defined in the FEM provide exact constraints compared to tests. However, friction movement may occur when the impact load is applied during experiments. This negligible movement is different from exact support conditions. These two factors lead to the numerical model experiencing more rigid behavior under impact load and cause a diversion between numerical and experimental results.

In the numerical analysis performed, the debonding behavior of the interface between TRM strips and concrete was modeled using a contact-based cohesive zone modeling approach. This modeling technique for the interface has been applied using the tiebreak function and Eq. 5. According to the authors' knowledge, the most advanced modeling technique for the interface belonging to the strengthened RC members subjected to dynamic load is a cohesive zone modeling approach. It has been commonly used in recent numerical studies [10]. However, it is explicit that debonding stress is strain-rate dependent. Since the authors do not encounter any strain-dependent mathematical model for the interface between TRM strips and concrete, debonding stress values are assumed constant as 10 MPa with the trial–error approach in the presence of the anchorage. The authors consider that the present FEM can better converge to experimental results by implementing the strain-dependent mathematical model developed in light of experiments representing the interface behavior. It is considered that the effective plastic strain distribution obtained from the software and presented in Fig. 13 will be safely utilized to evaluate the specimens' damage pattern. The fractures have generally concentrated around the impact loading region and distributed toward the supports. Effective plastic strain contours are substantially accordant with experimental damages and accurately reflect failure modes.

5 Conclusions

In the present study, a retrofitting method is developed to improve the general behavior and performance levels of RC slabs under impact load. An experimental program has been carried out to investigate the effectiveness of the present strengthening technique. The study has tried to develop a cost-effective and environmentally friendly

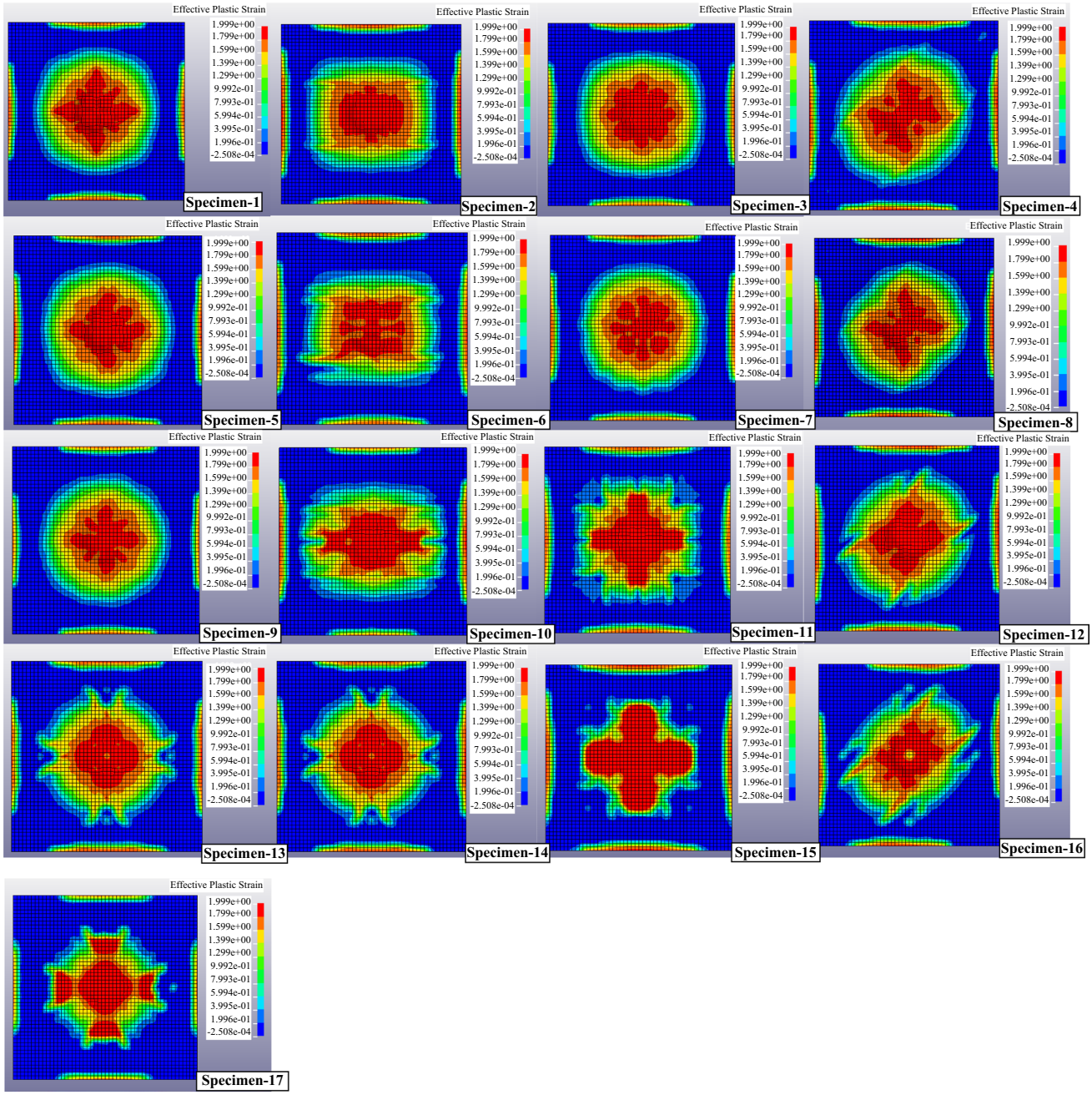


Fig. 13 Damage parameter distributions of test specimens obtained from finite element analysis

strengthening technique that can be easily applied within a short period using basalt TRM strips to develop the behavior of RC slabs under impact loads. The experimental variables investigated were the strengthening layout, widths of basalt TRM strips, and the effects of using BFRP fan-type anchors near the impact load application point. Under the impact loading with the same input energy, the time histories of the displacement, accelerations, strains, and impact loads acting on the RC slabs were recorded during tests to determine the performance level of the proposed strengthening technique. Besides, FEM has been introduced to evaluate the non-linear dynamic response of the RC slabs with TRM strips. After comparing experimental and numerical results, interpretations are made related to the extent to which the present FEM has successfully evaluated the impact response of the RC slabs with TRM strips. The findings obtained from the present study are summarized as follows:

Table 4 Comparison of experimental and numerical results

Spec #	Acceleration (g)					Maximum displacement (mm)			Residual displacement (mm)		
	Experimental		FEA		Ratio*	Experimental	FEA	Ratio**	Experimental	FEA	Ratio***
	Max	Min	Max	Min							
1	219	− 172	377	− 364	0.58	2.94	2.74	1.07	1.12	− 0.55	2.05
2	298	− 186	380	− 353	0.78	2.20	2.33	0.94	0.89	− 0.42	2.11
3	390	− 301	356	− 306	1.10	1.96	1.84	1.06	0.23	− 0.35	0.66
4	348	− 152	383	− 319	0.91	1.72	1.62	1.06	0.39	− 0.30	1.29
5	454	− 453	568	− 411	0.80	1.34	1.39	0.96	0.26	− 0.26	1.00
6	348	− 283	342	− 338	1.02	1.91	1.59	1.21	0.31	− 0.09	3.66
7	452	− 320	484	− 357	0.93	1.42	1.37	1.04	0.11	− 0.27	0.42
8	400	− 219	385	− 282	1.04	1.53	1.44	1.06	0.24	− 0.26	0.92
9	534	− 366	532	− 356	1.00	1.19	1.20	0.99	0.20	− 0.23	0.86
10	346	− 201	328	− 273	1.06	1.97	1.66	1.18	0.31	− 0.32	0.97
11	453	− 218	432	− 296	1.05	1.58	1.54	1.03	0.20	− 0.23	0.91
12	410	− 293	393	− 373	1.04	0.91	0.88	1.03	0.47	− 0.15	3.02
13	538	− 351	522	− 411	1.03	1.15	1.15	1.00	0.16	− 0.20	0.80
14	414	− 144	407	− 358	1.02	1.65	1.54	1.07	0.21	− 0.29	0.72
15	533	− 220	508	− 377	1.05	1.07	1.06	1.00	0.15	− 0.14	1.07
16	472	− 214	455	− 347	1.04	1.18	1.18	1.01	0.20	− 0.24	0.81
17	629	− 289	669	− 385	0.94	0.84	0.82	1.02	0.12	− 0.16	0.72

* Ratio of experimental maximum acceleration values to FEM results

** Ratio of experimental maximum displacement values to FEM results

*** Ratio of experimental residual displacement values to FEM results

- In the study, it is observed that the retrofitting method applied with basalt TRM strips significantly improved the general behavior and the performance of RC slabs under the effect of impact loading. The applied strengthening technique significantly enhanced the rigidity and stiffness of the RC slabs and correspondingly increased the maximum acceleration values that occur with the impact loading. Additionally, the maximum displacement and the maximum residual displacement decreased, and the applied strengthening technique significantly reduced the crack width and the number of cracks. It can be considered that a large extent of the possible damage is prevented through the strengthening technique. These results demonstrated that the strengthening technique applied with basalt TRM strips developed in this study remarkably increased the performance of RC slabs under the effect of impact loads.
- The increased width of the basalt TRM strips used in the retrofitting technique increased the maximum acceleration values and significantly decreased the maximum and residual displacement values. The retrofitting method applied with Basalt TRM strips increased the maximum acceleration values by an average of 101%. It decreased the maximum and permanent displacement values by an average of 57% and 66%, respectively.
- Bonding the basalt TRM strips in both directions on the RC slabs improved the behavior under the impact load more than the TRM strips bonded individually. In two ways, RC slabs retrofitted with basalt TRM strips exposed greater maximum acceleration values and much smaller maximum displacement and residual displacement than the specimens with TRM strips placed in a single way.
- The use of TRM strips in both directions for strengthening purposes increased the maximum acceleration values by 31% on average compared to using in one direction. It decreased the maximum displacement, permanent displacement, and maximum strain values by an average of 49%, 123%, and 36%, respectively.
- Bonding basalt TRM strips diagonally on the RC slabs increased the behavior under impact load more than bonding them orthogonally. The RC slabs retrofitted with basalt TRM strips diagonally have exposed greater maximum acceleration and lower maximum and residual displacement values than those retrofitted with basalt TRM strips orthogonally. The diagonal placement of basalt TRM strips attached to RC slabs for retrofitting increased the maximum acceleration values by 17% on average. It decreased the maximum displacement, permanent displacement, and maximum strain values by an

average of 32%, 69%, and 74%, respectively, compared to the orthogonal placement.

- In the retrofitting method improved in the present study, the use of BFRP fan-type anchors at the intersections of the TRM strips close to the impact point improved the behavior and performance of the specimens under the effect of impact loading. Specimens with anchorage exhibited greater maximum acceleration and less maximum and residual displacement values than those without anchorage. BFRP fan-type anchors in TRM strips used for retrofitting increased the maximum acceleration and maximum strain values by 18% and 12%, respectively. Using anchors caused the maximum and permanent displacement values to decrease by 25% and 50% on average, respectively.
- The comparison of experimental results and numerical solutions indicates, on average, 6%, 4%, and 29% differences for maximum acceleration, maximum displacements, and residual displacements, respectively.
- Within the scope of the study, the finite element analysis study performed with Ls-Dyna software showed that the behavior of reinforced concrete slabs under impact loading could be obtained at an acceptable rate in accordance with the experimental results. This is an extremely important result. As it is known, the realization of large-scale experiments of this type requires a long time, work, and a financial budget. With this computer simulation study, it has been shown that the general behavior of the reinforced concrete slabs tested can be obtained to a certain extent with the finite element models, and the detailed information necessary to do this is presented in the article. In light of this information, the reader is given important information about the finite element analysis models they can use in future parametric analysis studies. In summary, the finite element analysis study presented in this article contains important contributions to the literature, providing important information to the researchers working on this subject.
- The acceptable difference between numerical and experimental results stems from the non-homogenous nature of concrete and the support conditions. In the FEM model, it is impossible to exactly consider the non-homogenous structure of concrete, which occurs due to the environmental conditions, the care and cure conditions, and the compaction during the cast. Besides, exact support conditions in the FEM model do not reflect actual constraint behavior since some negligible movement may occur in parts composing supports during loading.
- The debonding phenomena occurring between TRM strips and concrete surfaces have been considered using a cohesive zone modeling approach. However, it is explicit that debonding stress is strain-rate dependent, and there is no advanced strain-dependent mathematical model for the interface between TRM strips and concrete that may reflect actual debonding behavior. Thus, debonding stress is assumed as 10 MPa since it provides the best convergence between numerical and test results.

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Data availability No data was used for the research described in the article.

Declarations

Conflict of interest All of the authors declare that he/she has no conflict of interest.

Ethical approval This article does not contain any studies with human participants or animals performed by any of the authors.

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