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Experimental and Numerical Investigation of Steel Sections under Impact Effect

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Research Paper

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Experimental and Numerical Investigation of Steel Sections under Impact Effect

Experimental and numerical behaviour of steel test specimens with various types of joints is investigated in this study. A drop weight test setup with necessary test equipment is used for this purpose. The mass and drop height of the hammer is taken to be constant so that the same impact energy can be applied on test specimens. The acceleration, displacement, impact load, drop numbers and drop durations, are obtained through experimental study. In addition, development of damage to test specimens is observed during tests. Numerical analyses of behaviour of test specimens under impact load are also conducted to verify test results using the Abaqus software, and a comparison of results is made.

Key words:
Impact effect, numerical analysis, steel material, test setup

Prethodno priopćenje

Engin Gücüyen, Erkan Kantar, R. Tuğrul Erdem, M. Berker Alıcıoğlu

Eksperimentalno i numeričko istraživanje čeličnih profila pri udarnom opterećenju

U radu se analizira eksperimentalno i numeričko ponašanje čeličnih ispitnih uzoraka s različitim vrstama priključaka. U tu svrhu korišten je uređaj s padajućim utegom. Kako bi se primijenila ista količina udarne energije na ispitne uzorke, masa i visina udarnog utega uzete su kao konstante. Eksperimentalnim istraživanjem dobivene su vrijednosti ubrzanja, pomaka, udarnog opterećenja, broja ispusta i trajanja pada. Tijekom ispitivanja pratilo se i širenje oštećenja na ispitnim uzorcima. Provedena je i numerička analiza ponašanja uzoraka uslijed udarnog opterećenja pomoću računalnog programa Abaqus te je napravljena usporedba rezultata.

Ključne riječi:
utjecaj udara, numerička analiza, čelični materijal, sustav za ispitivanje

Vorherige Mitteilung

Engin Gücüyen, Erkan Kantar, R. Tuğrul Erdem, M. Berker Alıcıoğlu

Experimentelle und numerische Untersuchung von Stahlprofilen unter Stoßbelastung

Die Arbeit analysiert das experimentelle und numerische Verhalten von Stahlprüfkörpern mit verschiedenen Verbindungsarten. Zu diesem Zweck wurde ein Fallgewichtsgerät verwendet. Um die gleiche Menge an Aufprallenergie auf die Probekörper aufzubringen, wurden Masse und Höhe des Aufprallgewichts als Konstanten genommen. Die Werte für Beschleunigung, Verschiebung, Stoßbelastung, Anzahl der Entladungen und Falldauer wurden durch experimentelle Untersuchungen erhalten. Die Ausbreitung von Schäden an den Probekörpern wurde ebenfalls während des Tests überwacht. Mithilfe des Computerprogramms Abaqus wurde eine numerische Analyse des Verhaltens der Probekörper aufgrund der Stoßbelastung durchgeführt und ein Vergleich der Ergebnisse abgeschlossen.

Schlüsselwörter:
Stoßauswirkung, numerische Analyse, Stahlwerkstoff, Prüfsystem

1. Introduction

Characteristics of structural steel arise from its composition and manufacturing procedure. Structural steel is used in almost all industries. Due to their homogenous and isotropic properties, structural steel sections are utilised in the construction of high-rise buildings, bridges, pedestrian overcrossings, and warehouses. When comparison is made with reinforced concrete structures, it can be seen that the weight of steel structures is lower because of high strength characteristics and elastic modulus. Thus, big spans can be overcome by smaller sections compared to other traditional types of material. As a result, a lighter and more economic structures, requiring less costly foundations, are obtained.

Steel material is the most often recycled material in the world [1]. There is no margin of error in the manufacture of steel structural members in factory conditions. Disassembly of steel members is fast and does not cause any change in material characteristics. Steel structures are designed to withstand major earthquakes due to ductility property of steel material, which enables plastic deformation without fracture.

Steel joints are structural elements that are utilized to join members in a structure. In practice, there are various types of joints. However, joints that consist of welded or bolted connections are most widely used in the field of structural engineering. These joints also enable load transfer. It is therefore important to select an appropriate method at the design phase.

Structural members are under the effect of various types of load during their service life. Static loads do not change over time. On the other hand, dynamic loads change in size, position or direction. Impact load is a significant type of dynamic load and its intensity may be higher compared to other load types. However, not many studies can be found in literature about the effect of impact on structural members. Although the effect of wind and seismic loads has been widely investigated, researchers usually avoid the analysis of impact effects due to difficult and costly testing. In recent years, the design of structures subjected to impact load has become increasingly popular owing to possible risks that are related to various accidental or natural hazards, such as vehicle accidents, explosions, rock falls, earthquakes, strong winds, and missile strikes [2-8]. The drop weight test setup is most often used to investigate behaviour of structural members exposed to low velocity impact loading. For this purpose, various test setups with measurement devices have been designed by researchers. The information about the impact test limits is provided in ASTM E 23 [9]. Thus, due to regulations provided in this standard, researchers are capable of improving performance of tests setups.

The authors experimentally investigated eight steel test specimens at two distinct impact energy levels [10]. In this study, four steel test specimens, produced using four different joint types, were principally subjected to impact loading. The mass of the steel hammer and drop height values were taken as constant during the experimental study. 14-kg steel hammer was dropped from a height of 1500 mm to implement impact load on test specimens. This means that a constant impact energy (14 x 9.81 x 1.5 = 206 J) was applied on the specimens. The experimental study of specimens was continued until failure damage, when maximum displacement occurred and bolts were separated from the connection regions of the specimens. Accelerometer, LVDT sensor, dynamic load cell, data logger, and optic photocells were used to measure and record data during the tests.

In addition to experimental study, incremental dynamic analyses were performed by the finite elements analysis software Abaqus to verify experimental results [11]. The acceleration, displacement and impact load values of test specimens were determined after analyses. These values are comparatively presented in acceleration-time, displacement-time, impact load-time and impact load-displacement graphs. In addition, stress distributions of test specimens were obtained by computer simulations. It is thought that experimental and numerical specimen testing results will be a significant contribution to the literature.

2. Experimental study

2.1. Test specimens and materials

Experimental part of this study involves four test specimens produced in a factory. Joint types are the variables of test specimens. Different joint types were used in the specimens because connection regions of profiles may present defects in production phase, such as weld defects and errors in end plates. Details of these joint types are presented in Figure 1. Rectangular shaped steel profiles measuring 40x80x3 mm were connected to each other. Besides, two end plates measuring 80 x 120 x 4 mm were utilized in the connection region of these profiles. Top and bottom flange parts of the profiles were welded to end plates by gas metal arc welding technique using wire 3 mm in thickness. Head bolts shown in Figure 2 were used to attach end plates to each other. The aim was to investigate specimens with defects in connection regions due to impact loading.

Each test specimen is 1000 mm long. Distances from the connection point of test specimens are presented in Figure 3. The steel grade S235JR with the density, minimum yield strength, tensile strength and elongation strain amounting to 7850 kg/m^3, 235 MPa, 360 MPa and 25 %, respectively, is utilized in the manufacture of steel profiles and end plates.

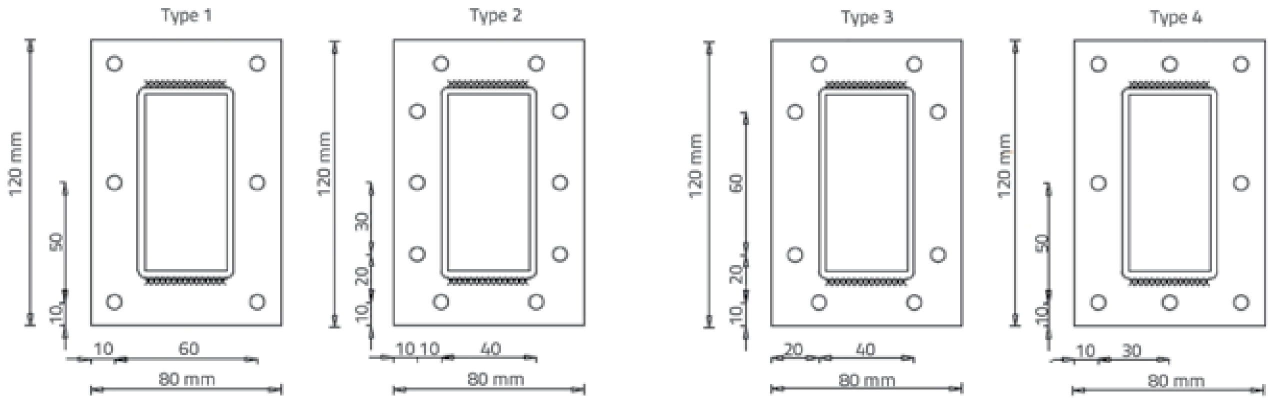

Figure 1. Joint types

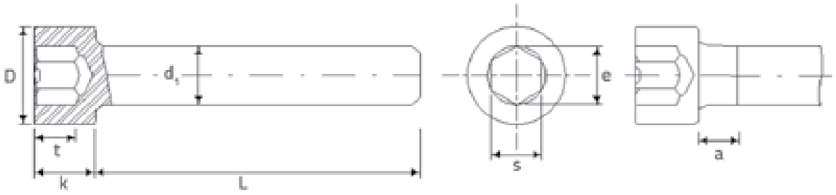

Figure 2. Bolts details

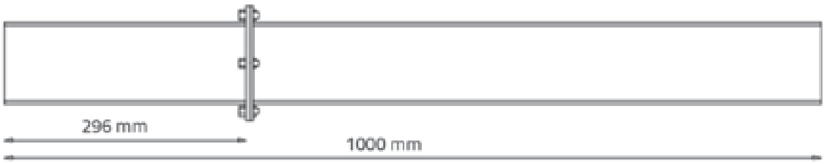

Figure 3. Length of test specimens

Connecting regions of test specimens are painted in yellow to enable better identification of damage situations. Details of the connecting regions are shown in Figure 4.

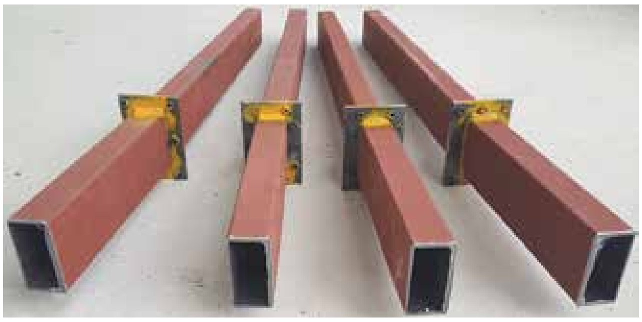

Figure 4. Details of test specimens

2.2. Test setup and equipment

Researchers have been developing drop weight test setups that are based on free falling movement of hammer from various drop heights [12-17]. The drop-weight test setup is widely used in impact experiments in which impact load is applied to test members. The studies show that the drop weight test setup with necessary measurement devices is the best way to determine impact resistance of test specimens. In this study, impact load is applied on test specimens by using a test setup presented in Figure 5 [18]. Necessary test equipment such as accelerometer, LVDT, load cell, data-logger, and optic photocells, was used in the test setup. The test setup is specially designed to determine behaviour of various materials or structural members under impact effect. The test setup allows weights of different magnitudes to be dropped from a maximum height of 2500 mm. In this way, potential energy is converted to kinetic energy at the moment of impact. The base platform measuring 1000 x 1000 x 200 mm, manufactured using high strength steel plates, was utilised in the test setup.

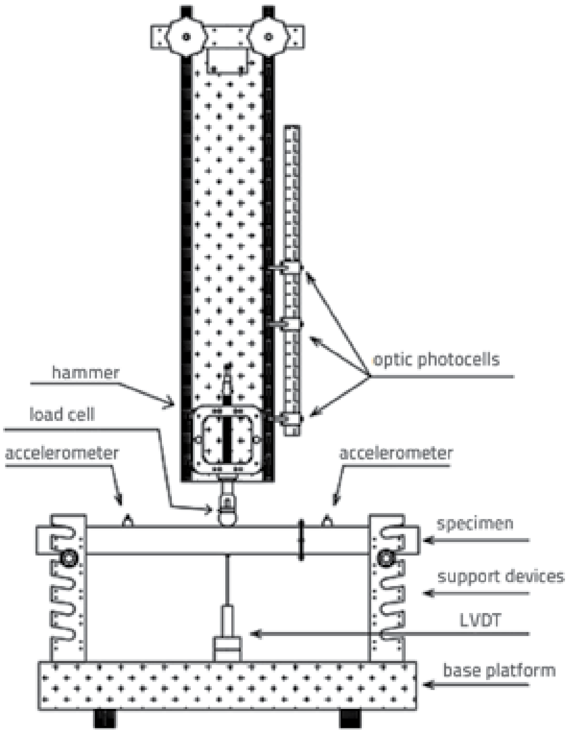

Figure 5. Schematic diagram of test setup

In the working phase of test setup, impact load is applied on test specimens by steel hammer dropped from a defined height. In this way, impact resistance of connecting regions is observed during the experimental study. Wheel-shaped members made of castermid material are used to place the hammer in test setup. In order to restrain horizontal and vertical movement in support regions, steel support devices measuring 100 x 430 mm are used in the experimental study.

Figure 6. Test specimen with equipment

Acceleration values are measured by two accelerometers that are symmetrically placed 250 mm away from the point of impact load. ICP type piezoelectric accelerometers are fixed on test specimens by brass devices with mechanical anchors. Accelerometers are also used to measure vibrations. The accelerometers selected for this test do not lose signal quality during impact tests. Measurement range of the accelerometers is ±4905 m/s², and the working temperature varies between -18 and +66° C.

Linear variable differential transformer (LVDT) is placed under the midpoint of test specimens to measure displacement values for each drop movement of steel hammer. Measurement range of LVDT is 50 mm, and a working temperature varies between -18 and +66 ° C.

The impact load caused by steel hammer is measured by ICP dynamic load cell during impact tests. The load cell is placed at the edge part of the steel hammer and it moves with the hammer during the drop movement. Large signals can be determined in short time spans by the load cell. Measurement range of the load cell is up to 88.96 kN, while its working temperature varies between -54 and +121 ° C.

As a sudden impact load is applied on test specimens, a special data-logger system is used to transfer measurement values from test devices in a short time. The data-logger has a 138 dB dynamic measurement range, 16 kHz maximum sampling speed, 24-bit ADC resolution and 12 VDC power input, with a working temperature varying between -20 and +50 ° C. Finally, the test data are converted into the acceleration-time, displacement-time, impact load-time, and impact load-displacement graphs by using a computer software.

Optic photocells are used to determine both drop numbers and drop durations during the tests. Drop durations are measured in milliseconds. The values are seen on the electronic screen of the test setup for each drop of steel hammer. A test specimen with necessary equipment is shown in test setup in Figure 6.

3. Test results

In this part of the study, test preparations are completed and impact tests on the specimens are performed. Special attention is paid that the hammer mass and drop height remain within the limits of measurement devices. In these impact tests, the mass of the hammer is 14 kg, and the drop height is 1500 mm.

Each test specimen, equipped with test devices, is placed in the test setup. Afterwards, support conditions are provided by using steel support devices. All test specimens, shown before application of impact load, are presented in Figure 7.

Development of damage to test specimens is observed during experimental study. Impact load is applied on test specimens until reaching failure in such a way that maximum midpoint displacements are obtained. After failure damage is observed, significant measurements can not be taken from test specimens because bolts are separated from the connection parts of the specimens. Failed specimens are shown in Figure 8.

Optic photocells are used to determine the number of drops and drop durations for each drop of steel hammer. The values can be seen on electronic screen forming part of test setup. Because constant impact energy is applied on test specimens, drop durations are almost similar for each specimen. Friction effects during drop movement of the hammer are thought to be the main reason of slight differences between drop durations. On the other hand, failure drop numbers differ

Figure 7. Test specimens in test setup

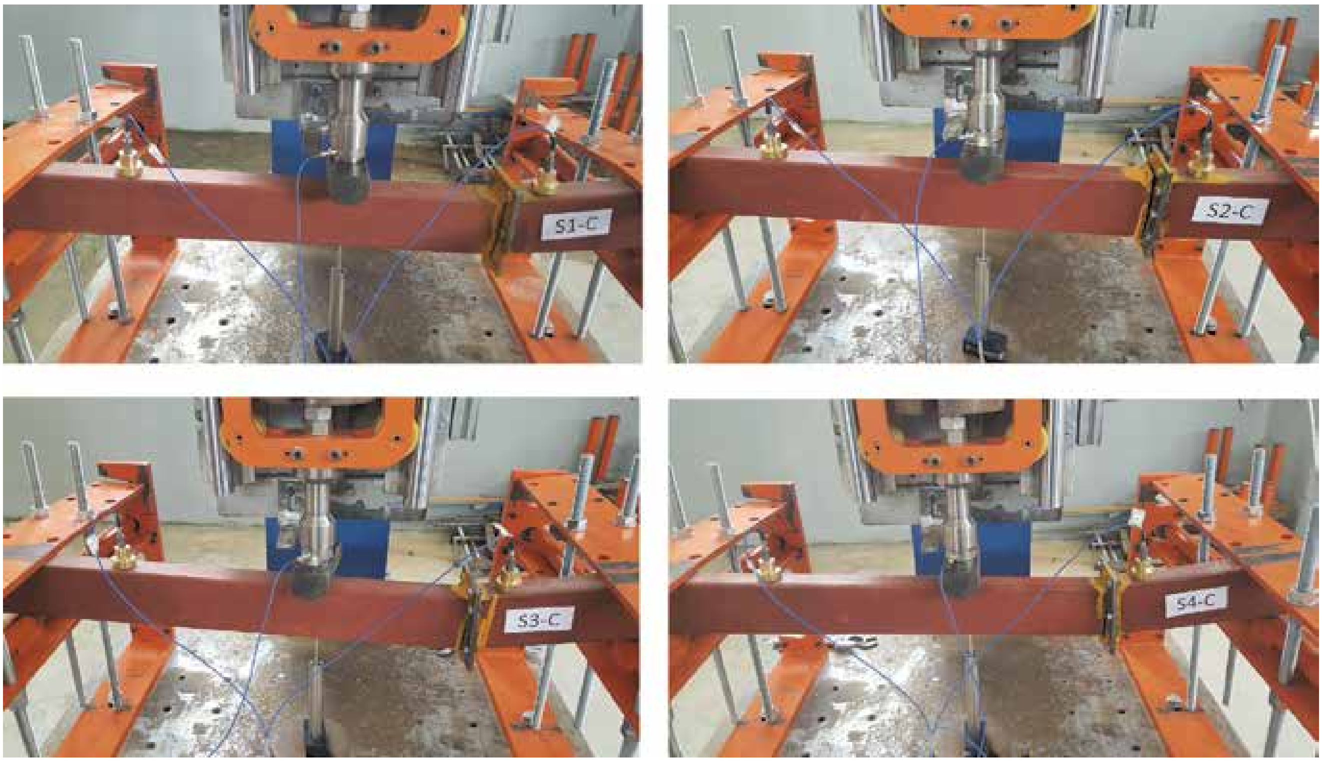

Figure 8. Failure damages of the specimens

from each other due to different joint types. The values are given in Table 1.

Table 1. Total drop numbers of specimens

Test specimen	Total drop number	Drop time [msec]
S1-C	7	613
S2-C	10	617
S3-C	7	611
S4-C	8	620

Figure 9. Test specimens after impact tests

The minimum and maximum acceleration, maximum displacement, and maximum impact load values are determined by measurement devices for each drop of steel hammer. After rebound movement of the steel hammer for each drop, the locking mechanism of the test setup is activated and the second strike is prevented. The results are presented according to first and failure drops in Table 2. In this way, the differences between measured values are obtained for undamaged specimens and failure damage of test specimens.

Maximum energy capacities of test specimens are determined by calculating the area under the impact-load displacement curves as given in Table 3. These curves are obtained by considering the impact load and displacement values of test specimens and will be comparatively presented in Section 4.

Table 3. Maximum energy capacities of test specimens

Specimen No.	Energy capacity [J]
S1-C	23.74
S2-C	26.83
S3-C	22.26
S4-C	24.35

Impact tests on specimens are completed when failure damage is observed for each test specimen. The configuration of bolts in the joints influenced failure damages of specimens. The bolts are separated from connection regions before the distance between them becomes bigger. All test specimens removed from test setup, with specimen damage in connecting regions, are presented in Figure 9.

4. Numerical analysis

The Abaqus finite element analysis software is utilized in numerical analysis to determine behaviour of test specimens under low velocity impact loading. As it provides various types of material models and enables successful conduct of a variety of analyses, Abaqus is widely used by researchers in the definition of numerical solutions [19-24]. Explicit module of the software, which gives accurate results under dynamic effects, is utilized for analyses. Besides, this module is appropriate

Table 2. Experimental results

Specimen No.	Acceleration [m/s^2]				Displacement [mm]		Impact load [kN]	
	First drop		Failure drop		First drop	Failure drop	First drop	Failure drop
S1-C	-1763.81	2017.38	-1065.83	1319.42	6.72	18.63	17.53	9.41
S2-C	-2249.66	2518.75	-1478.46	1385.97	5.89	15.75	19.92	10.27
S3-C	-2114.52	1827.46	-1292.68	1234.51	6.64	18.61	17.79	9.55
S4-C	-2336.74	2168.35	-1259.81	1426.33	6.21	16.84	18.86	9.86

Table 4. Comparison of acceleration and displacement values

Specimen No.	Acceleration [m/s^2]						Displacement [mm]		
	Test		Analysis		Test / Analysis		Test	Analysis	Test / Analysis
S1-C	-1763.81	2017.38	-2149.36	2198.27	0.82	0.92	6.52	6.08	1.07
S2-C	-2249.66	2518.75	-2417.65	2696.15	0.93	0.93	5.89	5.26	1.12
S3-C	-2114.52	1827.46	-2249.52	2058.33	0.92	0.89	6.91	6.01	1.15
S4-C	-2336.74	2168.35	-2231.48	2362.83	1.05	0.92	6.21	5.68	1.09
				Average:	**0.93**	**0.91**		Average:	**1.11**

Table 5. Comparison of impact load and energy values

Specimen No.	Impact load [kN]			Energy capacity [J]		
	Test	Analysis	Test / Analysis	Test	Analysis	Test / Analysis
S1-C	17.79	20.82	0.85	23.74	21.43	1.11
S2-C	19.92	22.73	0.88	26.83	24.52	1.09
S3-C	17.53	20.94	0.84	22.26	21.78	1.02
S4-C	18.86	21.66	0.87	24.35	23.26	1.05
		Average:	**0.86**		Average:	**1.07**

for characterisation of dynamic analyses. The first step of numerical analysis involves generation of three dimensional finite element models of test setup and specimens using the above mentioned software. For this purpose, C3D10M (10-node modified tetrahedron) shaped element types, which are suitable for simulation of impact problems, are used for all models. Afterwards, support conditions of test specimens are defined by considering boundary conditions in horizontal, vertical, and axial directions.

Because the problem is a free fall test, the only external force applied to steel hammer is the gravitational force. In addition, only vertical movement of the hammer is allowed in the software. Drop height and mass of the steel hammer are taken into account in the same way as in the experimental program. Linear elastic material model is used to define bolts, plates, and profiles, by considering the analysis time. Then, material characteristics are assigned to the related sections in the software.

Finite element models of geometries are separated into smaller pieces to obtain more accurate results. The finite element size is a significant parameter that directly effects the analysis results. For this reason, the mesh convergence analysis is performed for different element sizes to reach the most appropriate finite element size. Based on comparative and sensitivity analysis of results between 10 and 30 mm, the finite element size is set to 15 mm by taking into consideration the solution time, and the comparison between test and analysis results. The finite element model of S1-C test specimen is shown in Figure 10.

Time increments and time steps are other important parameters of the numerical analysis. Time increments and time steps are defined from the beginning to the end of the drop movement of steel hammer. As the problem is an incremental dynamic one, short time intervals are used to obtain proper results. So, the time increment is selected as 2x10^{-8} sec for 5000 time steps when the contact is established between hammer and test specimen. Numerical analyses are repeated for

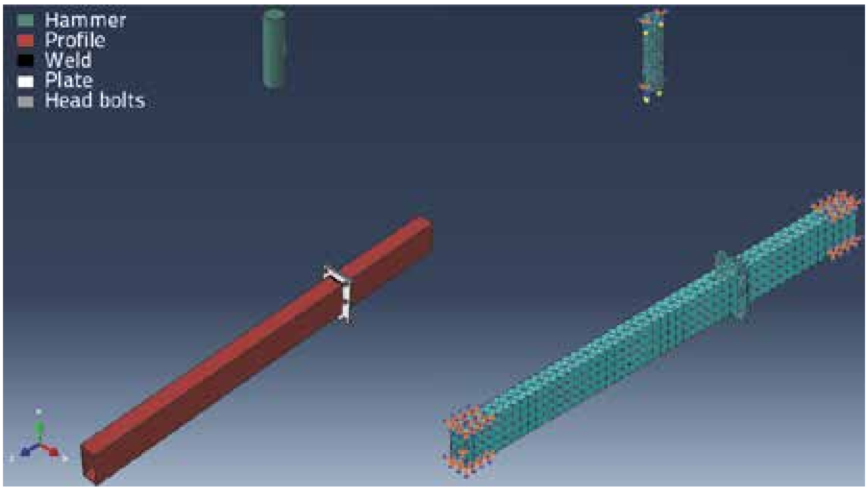

Figure 10. Finite element model of S1-C

the time increment and time step values until final values are reached.

Another issue is the simulation of contact surfaces in the software. The interaction property is used to provide a connection between related geometries. The surface to surface contact is selected for the surfaces of steel hammer and test specimen. The hammer surface that applies impact load on the test specimen is selected as master. The corresponding part of the test specimen is selected as slave in the analysis. Thus, the related surfaces are not permitted to penetrate each other. In the analysis, the interaction occurs through contact surfaces. The surface to surface contact property is utilized between contact surfaces. Besides, the behaviour of contact surfaces is taken as a tangential value in the software. On the other hand, the hammer rebound from the specimen is modelled by normal contact behaviour. Because it is not possible to remove friction effects during experimental program, the coefficient of friction amounting to 0.02 is adopted in the analysis.

To verify test results, incremental dynamic analyses are performed for the first drop movement of steel hammer using a high performance computer, which has enabled accurate and rapid determination of results. Thus, the acceleration, displacement and impact load values are compared for each test specimen in the following tables. The acceleration-time, displacement-time, impact load-time graphs are determined. Furthermore, the impact load-displacement graphs are determined for the same time interval to obtain the energy capacity values of test specimens. The graphs are presented for all test specimens in Figures 11 to 14.

Von Mises stress distributions are obtained for test specimens when impact load is transferred to specimens. In the experimental program, stress distributions are parallel to the development of damage on test specimens. Stress distributions are presented in Figure 15 for all specimens. The unit of stress used in the figure is Pa (N/m^2).

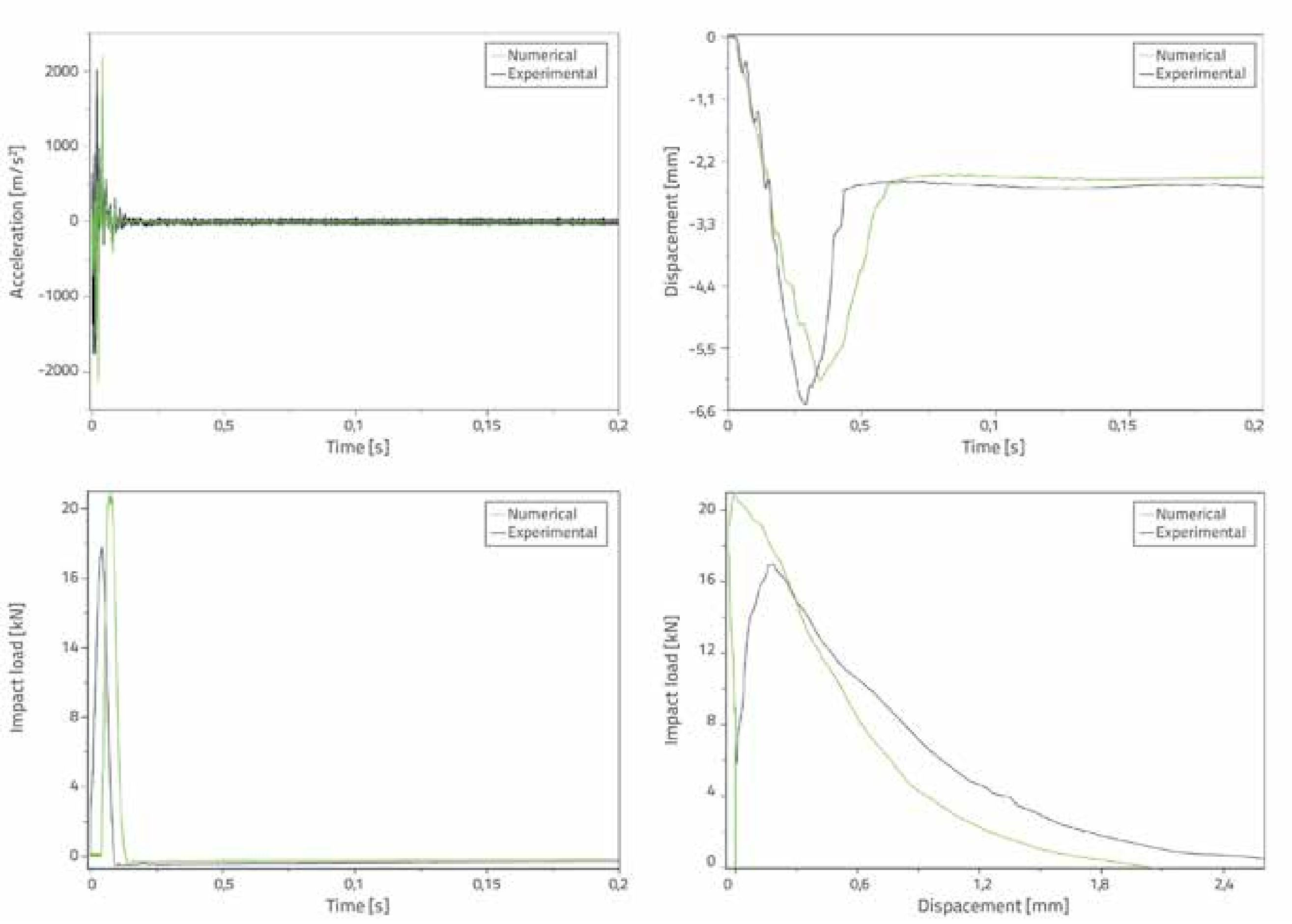

Figure 11. Graphs for S1-C test specimen

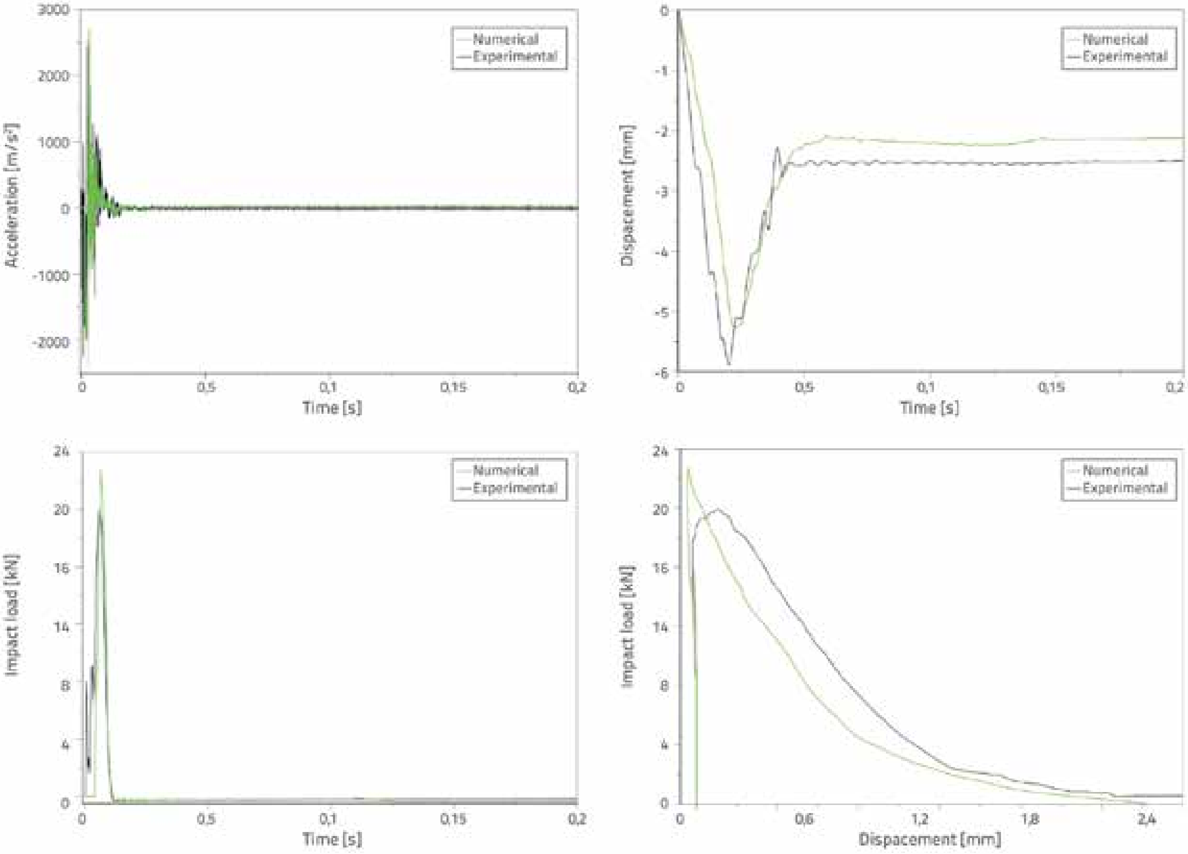

Figure 12. Graphs for S2-C test specimen

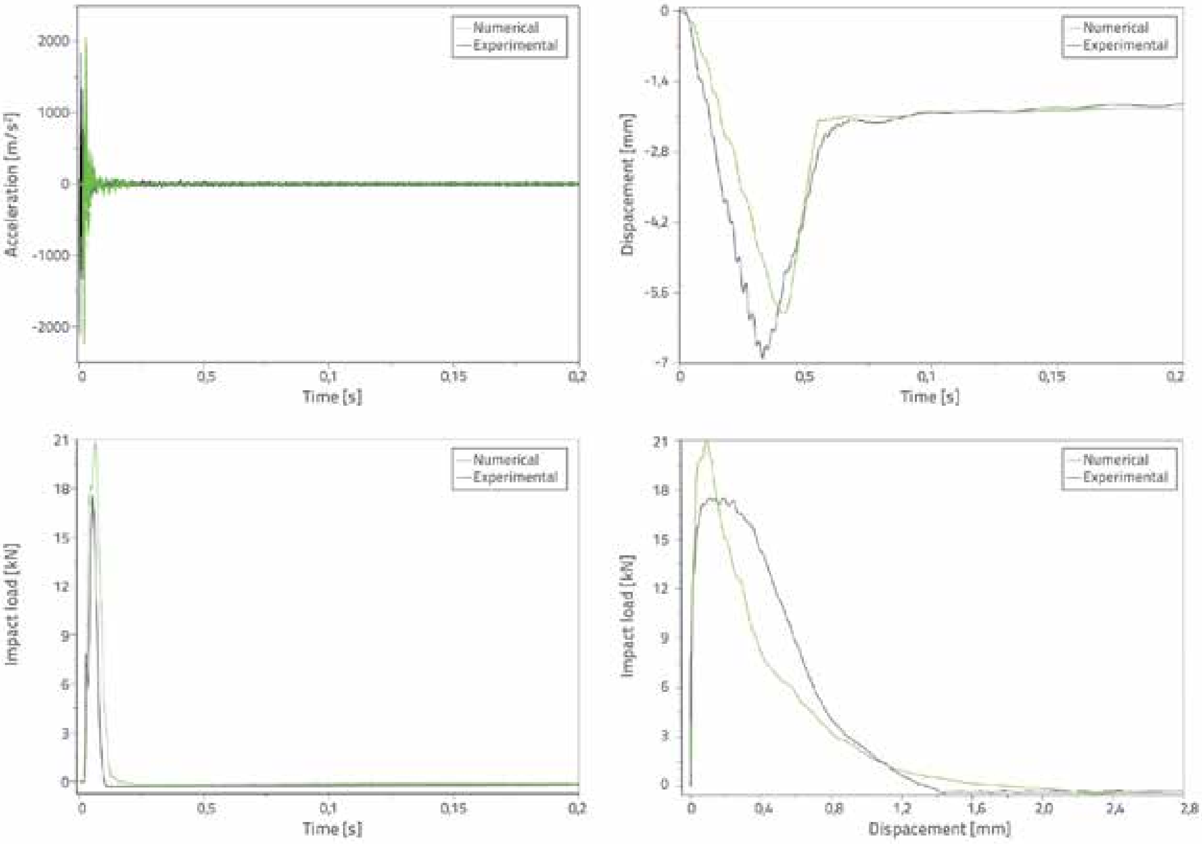

Figure 13. Graphs for S3-C test specimen

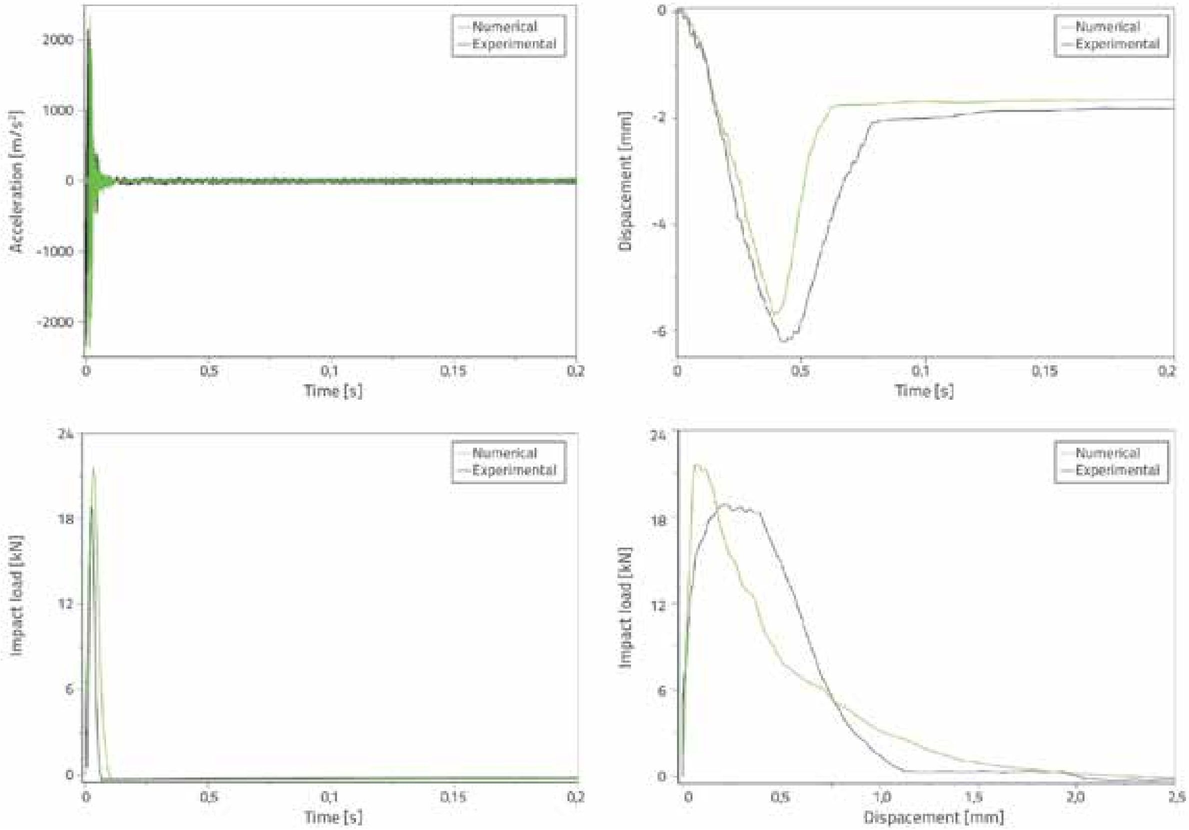

Figure 14. Graphs for S4-C test specimen

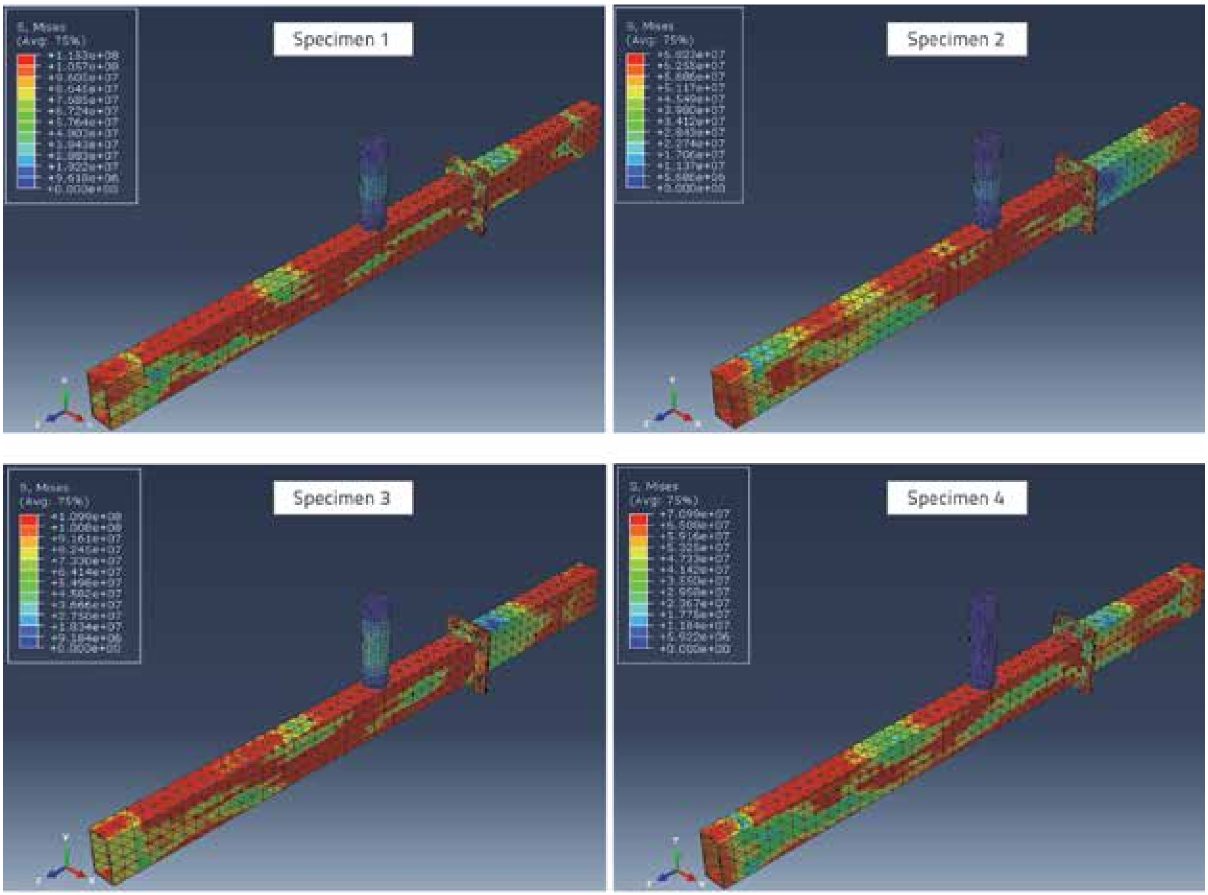

Figure 15. Von-Mises stress distributions

5. Conclusion

Structural steel is increasingly used in construction due to favourable developments in technology and materials science. However, it is important to design structural members that are resistant to various load conditions. For this purpose, researchers have been developing test setups that permit investigation of structural members under various loads. As, among all load effects, the impact load is the least known, it is usually ignored in the design of structures. Impact tests for structural members are based on several measurement devices. In addition, researchers have recently developed test setups aimed at determining behaviour of test specimens under impact effect.

In this study, steel-made test specimens with various types of joints were primarily tested under impact load. The mass and drop height values of steel hammer were taken to be constant so that the same level of energy can be applied on test specimens. Several test devices such as accelerometer, LVDT, load cell, optic photocells, and data logger, were used to determine behaviour of test specimens. Impact tests were continued until failure damage is observed on specimens. Key findings of the study are given below.

Acceleration values were measured by accelerometers from two symmetrical points for each drop movement of steel hammer. It was established that acceleration values decrease as the test specimens approach failure damage. Besides, the values were affected by the rigidity of test specimens due to joint types. Highest acceleration values were obtained for the test specimen S2-C that has 10 head bolts in the connection area.

Displacements were determined by LVDT sensors placed under the midpoint of the specimens. The biggest displacement values were registered for failure drop of steel hammer. When joint types were investigated, maximum displacement values were obtained for test specimens S1-C and S3-C, which were designed with 6 bolts placed close to one another. On the other hand, the minimum displacement value was obtained for S2-C specimen in both experimental and numerical studies.

Impact loads were measured by a dynamic load cell that was placed at the edge part of the hammer. While maximum values were obtained for the first drop, minimum values were determined for the failure drop of steel hammer. Load-displacement curves were generated by considering impact load and displacement values for the same time interval. So, energy capacities were calculated according to the area of load-displacement curves. The maximum energy capacity was obtained for the test specimen S2-C.

Numerical analyses were performed for each test specimen to verify test results. For this purpose, the explicit module of the finite elements analysis software Abaqus was used for incremental dynamic analyses. The test and analysis results were compared for the first hammer drop. Average values for the ratio of test and analysis results were also calculated. Besides, stress distributions of test specimens were determined. As expected, maximum stress values occurred around the impact point. Despite small discrepancies in the acceleration, displacement, impact load, and energy capacity values, a good correspondence was established between experimental and numerical results. It is considered that support conditions in the experimental program, and variation in analysis conditions, could be the reasons for such discrepancies. Finally, this study can additionally be improved by applying various levels of impact energy on test specimens.

Acknowledgements

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REFERENCES

[1] Singh, R.K., Murty, H.R., Gupta, S.K., Dikshit, A.K.: Development of composite sustainability performance index for steel industry, Ecological Indicators, 7 (2007) 3, pp 565-588.

[2] Kyei, C., Braimah, A.: Effects of transverse reinforcement spacing on the response of reinforced concrete columns subjected to blast loading, Engineering Structures, 142 (2017), pp. 148-164.

[3] Remennikov, A.M., Kong, S.Y., Uy, B.: Response of foam- and concrete-filled square steel tubes under low-velocity impact loading, Journal of Performance of Constructed Facilities, 25 (2011) 5, pp. 373-381.

[4] Al-Zubaidy, H., Al-Mahaidi, R., Zhao, X.L.: Experimental investigation of bond characteristics between CFRP fabrics and steel plate joints under impact tensile loads, Composite Structures, 94 (2012) 2, pp. 510-518.

[5] Yılmaz, T., Kıraç, N., Anil, Ö., Erdem, R.T., Kaçaran, G.: Experimental investigation of impact behaviour of rc slab with different reinforcement ratios, KSCE Journal of Civil Engineering, 24 (2020) 1, pp. 241-254.

[6] Yousuf, M., Uy, B., Tao, Z., Remennikov, A., Liew, J.Y.R.: Impact behaviour of pre-compressed hollow and concrete filled mild and stainless steel columns, Journal of Constructional Steel Research, 96, (2014), pp. 54-68.

[7] Park, H.: Investigation on low velocity impact behavior between graphite/epoxy composite and steel plate, Composite Structures, 171 (2017) 1, pp. 126-130.

[8] Gruben, G., Langseth, M., Fagerholt, E., Hopperstad, O.S.: Low-velocity impact on high-strength steel sheets: An experimental and numerical study, International Journal of Impact Engineering, 88 (2016), pp. 153-171.

[9] ASTM E23-00, Standard test methods for notched bar impact testing of metallic materials, ASTM International, West Conshohocken, PA, (2002).

[10] Erdem, R.T., Kantar, E., Gücüyen, E., Alıcıoğlu, M.B.: Experimental study on different joint configurations of rectangular hollow sections under impact loading, Gradevinar, 72 (2020) 5, pp. 401-410, https://doi.org/10.14256/JCE.2776.2019

[11] ABAQUS User's Manual, Version 6.12, SIMULIA, Dassault Systèmes Simulia Corp., 2015.

[12] Erdem, R.T., Gücüyen, E., Kantar, E., Bağcı, M.: Impact effect on different sized reinforced concrete specimens, Indian Journal of Engineering and Materials Sciences, 22 (2015), pp. 597-603.

[13] Othman, H., Marzouk, H.: An experimental investigation on the effect of steel reinforcement on impact response of reinforced concrete plates, International Journal of Impact Engineering, 88 (2016), pp. 12-21.

[14] Weiyi, Z., Quanquan, G., Xuqianq, D., Yao, Z., Yinghua, Y.: Impact response of steel-concrete composite panels: Experiments and FE analyses, Steel and Composite Structures, 26 (2018) 3, pp. 255-263.

[15] Erdem, R.T., Gücüyen, E., Kantar, E., Bağcı, M.: Impact behavior of concrete beams, Gradevinar, 66 (2014) 11, pp. 981-986.

[16] Zhao, W., Guo, Q.: Experimental study on impact and post-impact behavior of steel-concrete composite panels, Thin-Walled Structures, 130 (2018), pp. 405-413.

[17] Kadhim, M.M.A., Wu, Z., Cunningham, L.S.: Experimental study of CFRP strengthened steel columns subject to lateral impact loads, Composite Structures, 185 (2018) 1, pp. 94-104.

[18] Kantar, E., Erdem, R.T., Gücüyen, E., Alıcıoğlu, M.B.: Investigation of imperfect steel connections under impact effect, Scientific Research Project, Manisa Celal Bayar University, (2019).

[19] Kantar, E., Anil, Ö.: Low velocity impact behavior of concrete beam strengthened by CFRP strip, Steel and Composite Structures, 12 (2012) 3, pp. 207-230.

[20] Bambach, M.R.: Design of hollow and concrete filled steel and stainless steel tubular columns for transverse impact loads, Thin Walled Structures, 49 (2011) 10, pp. 1251-1260.

[21] Al-Thairy, H., Wang, Y.C.: A numerical study of the behaviour and failure modes of axially compressed steel columns subjected to transverse impact, International Journal of Impact Engineering, 38 (2011) 8-9, pp. 732-744.

[22] Ahmed, A.: Modeling of a reinforced concrete beam subjected to impact vibration using ABAQUS, International Journal of Civil and Structural Engineering, 4 (2014) 3, pp. 227-236.

[23] Gilbert, B.P., Rasmussen, K.J.R.: Impact tests and parametric impact studies on drive-in steel storage racks, Engineering Structures, 33 (2011) 5, pp. 1410-1422.

[24] Iqbal, M.A., Kumar, V., Mittal, A.K.: Experimental and numerical studies on the drop impact resistance of prestressed concrete plates, International Journal of Impact Engineering 123 (2019), pp. 98-117.