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Experimental study on hollow section joints under impact loading

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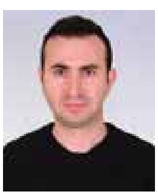

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Research paper

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Experimental study on hollow section joints under impact loading

Steel sections with four different joint types, subjected to sudden impact, are investigated in this study. A drop weight test setup was developed for this purpose. Impact tests were performed for two different energy levels. Acceleration-time, displacement-time, impact load-time, and impact load-displacement graphs were developed and presented. It was established that the behaviour of test specimens is affected by joint types and impact energy applied. Failure damage situation occurs earlier when rigidity of specimens decreases and when higher level of impact energy is applied.

Key words:
damage development, energy level, impact effect, joint type, test setup

Prethodno priopćenje

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

Eksperimentalno istraživanje spojeva od šupljih profila pri udarnom opterećenju

U ovom se radu analizira udarna otpornost čeličnih profila s četiri različite vrste priključaka. Za te je potrebe razvijeno ispitivanje uređajem s padajućim teretom. Ispitivanja otpornosti na udarno opterećenje provedena su za dvije razine energije. Izrađeni su i prikazani dijagrami ubrzanja i vremena, pomaka i vremena, udarnog opterećenja u vremenu te odnosa udarnog opterećenja i pomaka. Utvrđeno je da na ponašanje uzoraka utječe vrsta priključka i nanesena udarna energija. Do sloma oštećenjem dolazi ranije kod niže krutosti uzoraka te pri nanošenju više razine udarne energije.

Ključne riječi:
razvoj oštećenja, razina energije, utjecaj udara, vrsta priključka, izvedba pokusa

Vorherige Mitteilung

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

Experimentelle Untersuchung von Verbindungen aus Hohlprofilen bei Stoßbelastung

In dieser Abhandlung wird die Schlagfestigkeit der Stahlprofile mit vier unterschiedlichen Verbindungsarten analysiert. Zu diesem Zweck wurde ein Dropdown-Gerätetest entwickelt. Der Festigkeitstest auf Schlagbelastung wurde für zwei Energieniveaus durchgeführt. Ausgearbeitet und dargestellt werden Diagramme der Beschleunigung und der Zeit, der Verschiebung und Zeit, der Schlagbelastung in der Zeit sowie das Verhältnis der Schlagbelastung und der Verschiebung. Festgestellt wurde, dass das Verhalten der Proben von der Verbindungsart und der zugefügten Schlagenergie beeinflusst wird. Das Versagen durch Beschädigung tritt bei geringerer Probesteifigkeit früher auf sowie bei höherem Schlagenergieniveau.

Schlüsselwörter:
Entwicklung von Beschädigung, Energieniveau, Schlagauswirkung, Verbindungsart, Durchführung von Experimenten

1. Introduction

Recent developments in the field of civil engineering have been made possible thanks to progress in technology and materials science. It is important to have an appropriate knowledge about advantages and disadvantages of construction materials. Structural steel is a homogenous and isotropic material. Besides, another useful characteristic of steel is its ductility. Thus, steel materials can be applied in plastic design. Steel also exhibits some other significant properties such as high tensile strength, durability, and low weight. Consequently, steel structures are lighter than traditional reinforced concrete structures and they therefore constitute an optimum solution in terms of seismic load and ground subsidence.

Structural steel members are manufactured in factory conditions. Assembly operations can therefore be performed at construction site. These members are not affected by adverse weather conditions and they can be assembled in a short period of time. In addition, it is easy to reinforce or change structural members in steel structures. Structural members can be disassembled and used in another structure without any loss. Because of these general properties, structural steel has several advantages when compared to other materials that are used in civil engineering.

Steel joints, which are usually made of bolts, welds and plates, are utilized to connect the elements that constitute the structure. These joints also provide for load transfer between elements. Due to the main task of these steel joints, strict attention must be paid at the manufacturing stage.

Many structures have been built using steel material, e.g. high-rise buildings, industrial structures, bridges, pedestrian overcrossings, towers, etc. These structures provide service for a large variety of purposes. Steel structures are subjected to different load combinations during their service life. The effects of static load on structures are permanent. On the other hand, dynamic loads happen suddenly and affect the structure in a short span of time.

Impact load is a sudden dynamic load whose effect may be greater when compared to other load types. The impact effect occurs at the moment of collision between objects. So, very high stress values are imposed on objects at that moment. Typical impact incidents include sudden explosions, strong winds, vehicle accidents, projectile and missile strikes, rock falls, and crane accidents. For this reason, impact effects are taken into consideration in specific cases [1].

When studies presented in literature are investigated, it can be seen that very few of them deal with impact behaviour of steel members [2-7]. Zeinooddini et al. conducted a numerical simulation of impact tests. Bambach et al. reported on the low velocity impact behaviour of steel sections. Wang et al. studied experimentally and numerically the performance of concrete filled steel tubular members. Kidd et al. performed numerical analyses to validate experimental results of steel connections subjected to drop hammer testing. Fras et al. investigated the complexity of impact conditions and their influence on the fracture of high strength steel. Zhu et al. developed a test apparatus and investigated, both experimentally and numerically, the behaviour of CFST columns and connections. Researchers agree that the drop weight test setup is the best way to perform impact tests. Different test setups have therefore been developed to investigate behaviour of different materials and structural members under impact [8-11]. In addition, several test devices have been utilized in test setups to take measurements at the very places in which impact load becomes effective. Performance of tests setups has been improved by researchers owing to ASTM E 23 regulations in which information about impact test limits is given [12].

The aim of this study is to investigate behaviour of test specimens under impact load. The main problem is to perform impact tests on specimens manufactured with different joint types. As connection zones of the profiles may be defective due to some production-related reasons such as weld defects and errors in end plates, various configurations have been utilized in specimen joints.

A test setup has been developed for the experimental study. Besides, several test devices such as accelerometer, LVDT, load cell, data logger, and optic photocells are used in the experimental study. Another important point of the study is the difference between the measurement limits of test devices. The mass of the hammer is constant and amounts to 14 kg, while drop heights are 1000 mm and 1250 mm in impact tests. As structural members can be affected by various impact incidents in practice, two different energy levels have been applied to observe the response of test specimens. After completing the experimental study, test results are compared by considering the joint type and drop height, and the behaviour of test specimens is then interpreted.

2. Experimental study

2.1. Test specimens and materials

Dimensions of rectangular steel profiles that are connected to each other are 40x80x3 mm. Two end plates measuring 80x120x4 mm were used in the connection zone of steel profiles. Top and bottom flange parts of the profiles were welded to end plates by gas metal arc welding technique with 3 mm in thickness. The impact resistance of test specimens having defective connection regions was investigated in this way. On the other hand, end plates were connected to each other by hex socket head bolts. A schematic view of these bolts is given in Figure 2, while properties are presented in Table 1. [13].

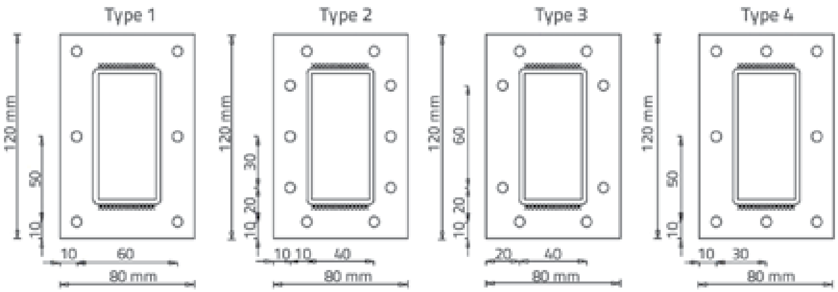

Figure 1. Joint types

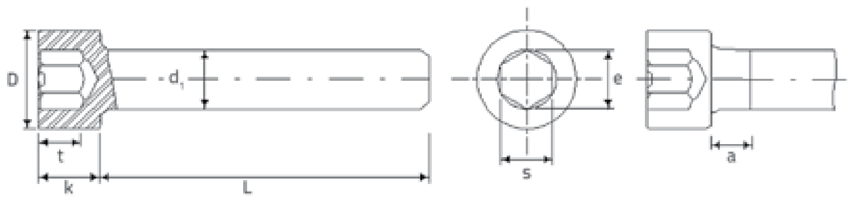

Figure 2. Schematic view of the bolts

Table 1. Properties of hex socket head bolts

Property	Value
d_1 [mm]	6.00
a_{max} [mm]	3.00
S [m]	5.00
e_{min} [mm]	5.72
K [mm]	6.00
D [mm]	10.00
L [mm]	18.00
t_{min} [mm]	3.00
Yield strength [N/mm^2]	640
Tensile strength [N/mm^2]	800

The length of test specimens is constant and amounts to 1000 mm. Test specimen details are shown in Figure 3. The steel grade S235JR is used in the production of steel profiles and end plates. Mechanical characteristics of S235JR are presented in Table 2. [14].

Figure 3. Detail of a test specimen

Table 2. Mechanical characteristics of S235JR

Characteristic	Value
Density [kg/m^3]	7850
Minimum yield strength [MPa]	235
Tensile strength [MPa]	360
Elongation strain [%]	25

Before performing impact tests in the scope of the experimental program, all test specimens were prepared according to joint types, as shown in Figure 4. Various configurations with regard to the number of bolts were used in connection regions of the specimens. Joints were marked by yellow colour to enable better observation of damage development.

Figure 4. Test specimens

2.2. Measurement devices

Impact tests were performed using a test setup specially designed for such experiments. Many researchers have used similar test setups for various specimens, as shown in relevant literature [15-21]. It can be seen that the free fall drop weight test setup has been most frequently used by researchers. In this test setup, a specific mass is dropped from a certain height onto the test specimen. Impact loading is applied on test specimens by a striker, usually named hammer, and impact resistance of specimens is investigated after testing. The base platform of the designed test setup was made of high strength steel plates.

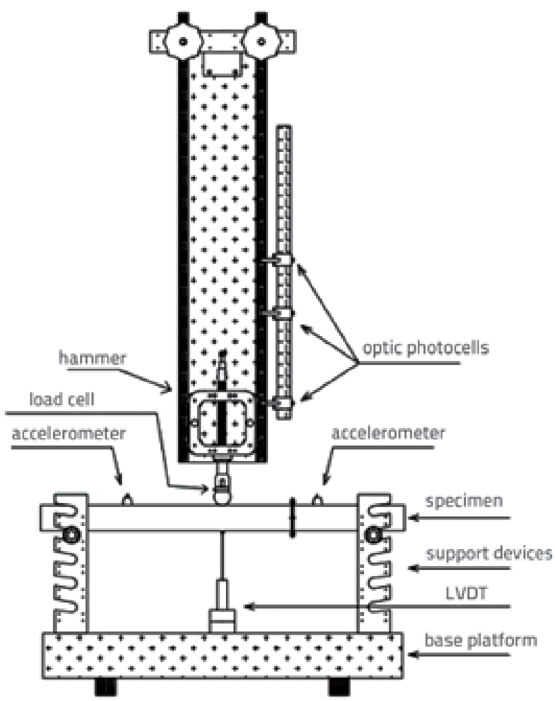

Figure 5. Test setup

Dimensions of the base platform were 1000x1000x200 mm. Several measurement devices, such as the accelerometer, LVDT, force sensor, data-logger, and optic photocells, were used during impact tests. A schematic view of test setup is presented in Figure 5.

According to the test setup, the impact load is applied on test specimens by a steel hammer from two different drop heights. In this way, different levels of impact energy are obtained due to the change of drop height. Steel hammer measuring 200x200 mm is placed between two slides in the test setup. The distance between these slides is 200 mm.

Steel hammer, whose mass is taken as constant during the testing, is connected to test setup by 4 wheel shaped members that are made of castermid material. Test specimens are supported by steel support devices measuring 100x430 mm at both ends. Thus, rotations and horizontal and vertical movements in supported zones of test specimens are restrained. Details of steel hammer and support devices are shown in Figure 6.

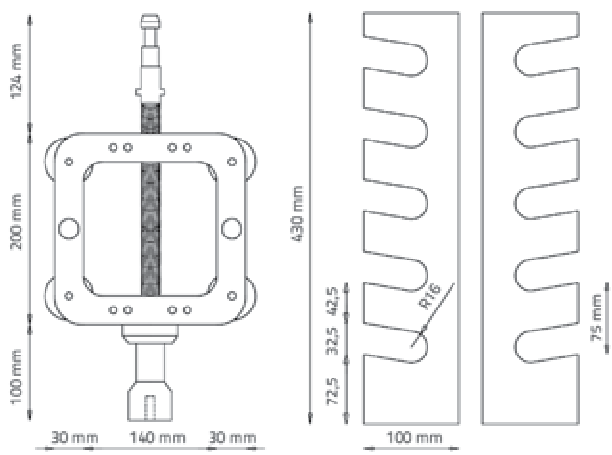

Figure 6. Details of hammer and support device (mm)

Because measurement limit of the accelerometers is exceeded when they are located close to impact point, two accelerometers are symmetrically placed at 250 mm from the impact point. ICP piezoelectric accelerometers are utilized to measure acceleration values during tests. These accelerometers are fixed on test specimens by using special brass devices to obtain reliable results without any loss. The accelerometers can measure any vibration without losing quality of the signal. The measurement range, sensitivity, and frequency of the accelerometers amount to ±98000 m/s², 0.05 mV/(m/s²) and 0.2-25000 Hz, respectively.

Linear variable differential transformer (LVDT) is used to measure displacement values for each drop. Because maximum displacements occur around the zone where the impact load is applied, the LVDT is placed under the midpoint of test specimens. Measurement range of LVDT is 50 mm at the working temperature varying from -18 to +66°C.

The ICP dynamic load cell is placed at the edge part of the steel hammer in order to measure impact load. Sudden effects are accurately measured by this sensor. The measurement range of the load cell is up to 88.96 kN and the working temperature varies between -54 and +121 °C.

Test data are collected by data logger having a sampling rate of 200 kHz. Afterwards, the data are transferred to computer and evaluated by special Dewesoft X3 software. This software enables recording and digitization of test data. Finally, time histories of acceleration, displacement, and impact load are determined.

Drop numbers and durations are registered by optic photocells in the experimental study. These values are seen at the electronic screen forming part of the test setup. A test specimen with measurement devices is shown in Figure 7.

Figure 7. A test specimen in the test setup

3. Test results

Test specimens are first divided into 4 groups according to joint type. Besides, change in drop height is the other variable in the experimental study. Properties of test specimens are given in Table 3.

Table 3. Properties of test specimens

Test specimen	**Joint type**	**Mass of the hammer** [kg]	**Drop height** [mm]
S1-A	1	14	1000
S2-A	2	14	1000
S3-A	3	14	1000
S4-A	4	14	1000
S1-B	1	14	1250
S2-B	2	14	1250
S3-B	3	14	1250
S4-B	4	14	1250

Figure 8. Failure damage situations

Impact tests on test specimens are performed until the failure damage situation is reached. Maximum displacement occurs and test specimens are unable to resist impact load in such failure damage situation. It is therefore impossible to take reliable measurements by test devices after failure damage. Failure damage situations for test specimens in case of 1250 mm drop height are presented in Figure 8. Number and duration of weight drops for each test specimen are determined by optic photocells and can be simultaneously seen on the electronic screen forming part of the test setup. Impact tests are finished when a failure damage situation is observed. Total drop numbers and drop times in milliseconds are given in Table 4 for each test specimen. It can be observed that joint types of the specimens cause differences in the number of drops for the same drop height.

Table 4. Total drop numbers of specimens

Test specimen	Total drop number	Drop time [msec]
S1-A	16	495
S2-A	19	490
S3-A	17	492
S4-A	17	489
S1-B	12	561
S2-B	15	557
S3-B	12	554
S4-B	14	559

Table 5. Experimental results

Test specimen	Acceleration [m/s²]				Displacement [mm]		Impact load [kN]	
	First drop		Failure drop		First drop	Failure drop	First drop	Failure drop
S1-A	-1271.34	1361.82	-826.54	991.29	3.88	10.83	11.68	7.74
S2-A	-1568.49	1792.17	-1175.73	1018.94	2.61	8.05	13.51	8.63
S3-A	-1507.61	1317.94	-1028.25	920.83	3.57	10.34	12.07	8.03
S4-A	-1618.23	1447.38	-918.37	1157.61	3.05	8.93	12.85	8.19
S1-B	-1617.61	1457.33	-1124.26	981.49	4.93	14.19	14.26	8.68
S2-B	-2024.36	1886.55	-1259.38	1324.27	3.51	11.94	16.49	9.51
S3-B	-1511.83	1694.27	-994.85	1231.53	4.64	11.88	14.81	8.71
S4-B	-1894.67	1604.92	-1355.73	1087.82	3.91	13.31	16.09	9.24

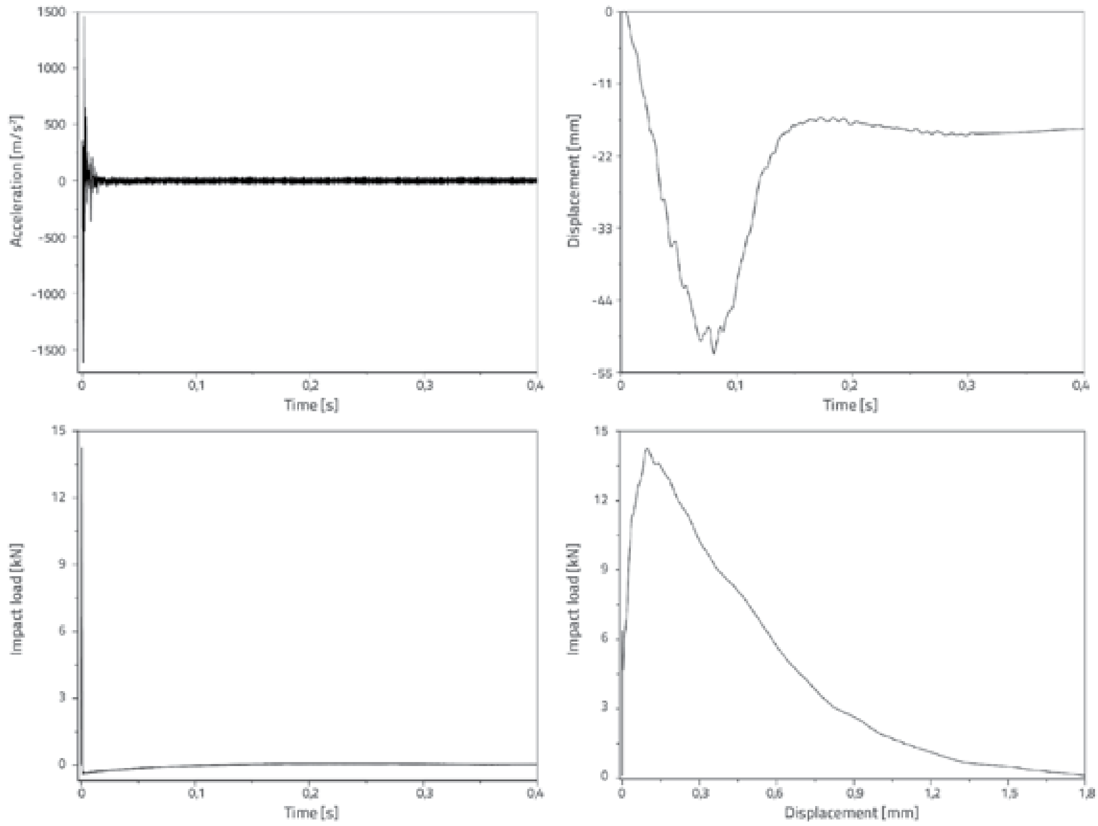

Figure 9. Test results for S1-B test specimen

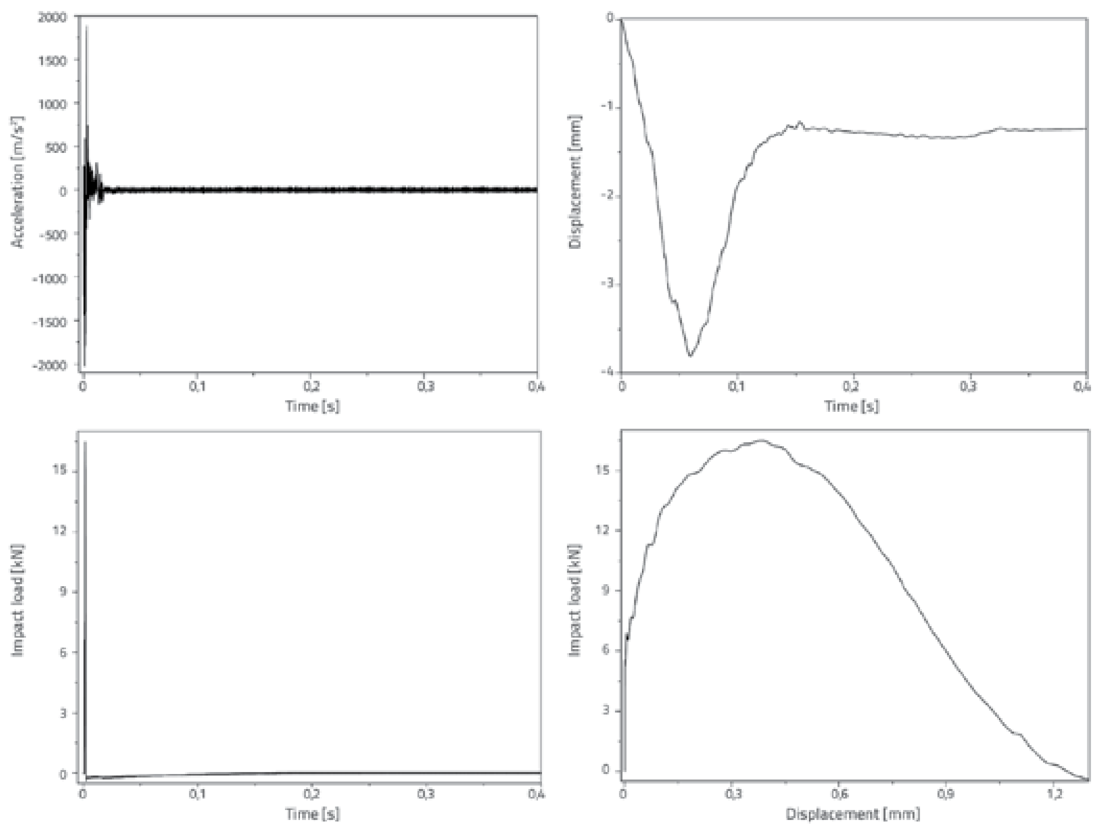

Figure 10. Test results for S2-B test specimen

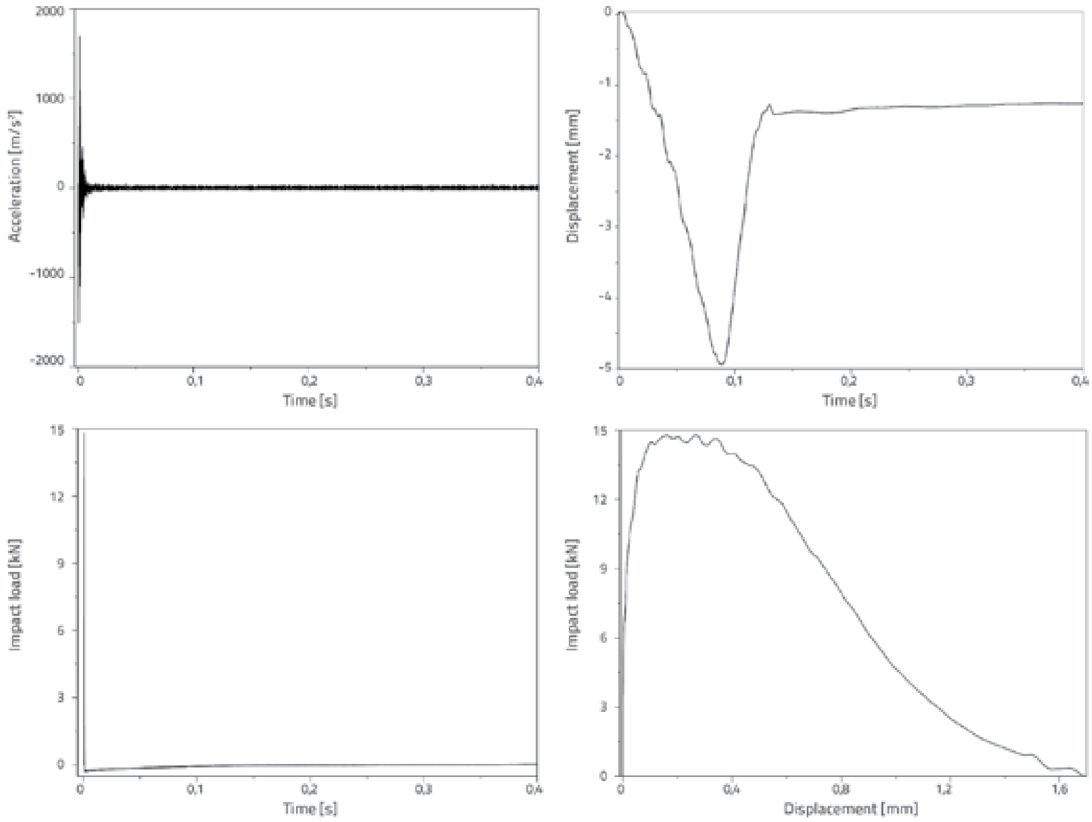

Figure 11. Test results for S3-B test specimen

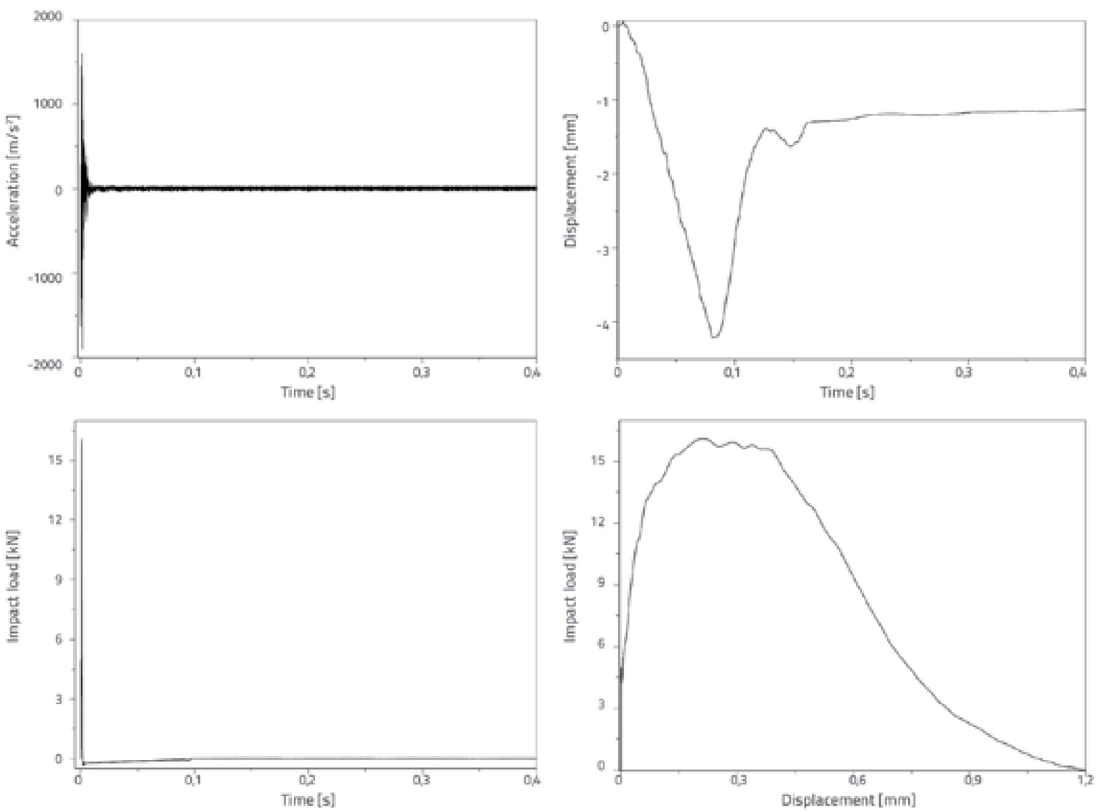

Figure 12. Test results for S4-B test specimen

The acceleration, displacement and impact load values are obtained by measurement devices from the first drop to the final drop of the steel hammer. Since acceleration values are measured from two symmetrical points of test specimens, bigger values are taken into consideration. Measured values for the first drops and failure drops of steel hammer are presented in Table 5 so as to represent the undamaged and failure behaviour of test specimens.

The acceleration-time, displacement-time and impact load time histories are utilized to investigate the behaviour of specimens subjected to impact load. Besides, impact load-displacement graphs are determined for the same time interval to see the energy capacity values of test specimens. The graphs shown in Figures 9 to 12 are related to the first drop of the 14 kg steel hammer on the specimens S1-B, S2-B, S3-B and S4-B from the height of 1250 mm.

After determining the impact load and displacement values of test specimens, maximum energy capacities are calculated by considering the area covered by impact-load displacement curves. The results are given in Table 6 for each test specimen.

Table 6. Maximum energy capacities of test specimens

Specimen No.	Energy capacity [J]
S1-A	11.53
S2-A	14.96
S3-A	12.78
S4-A	14.65
S1-B	16.27
S2-B	19.58
S3-B	16.76
S4-B	18.92

Figure 13. Test specimens after impact tests

The experimental program is considered completed when all test specimens reach the failure damage situation. Test specimens are shown together so as to present the failure damage situations according to joint type and drop height, as shown in Figure 13. Bolts are separated from joint region of test specimens. Thus, the specimens can not withstand the impact load in the failure damage situation.

4. Conclusion

The impact load, which can be defined as a type of impulsive dynamic load, is usually being ignored in the design of structural members. Because impact load is a specific loading situation, and as complicated design and analysis steps are required when studying the effect of impact on structural members, it is only recently that appropriate test setups have been developed by researchers. The operating mechanism of such test setups involves dropping an appropriate mass from a specified height, and then taking measurements by means of adequate test devices.

The experimental behaviour of steel test specimens equipped with various types of joints was investigated in this study. For this purpose, a special test setup was designed and necessary measurement devices such as accelerometers, load cell, LVDT, optic photocells and data logger, were used. In the experimental program, two different energy levels were applied on test specimens through the change in drop height values. In addition, development of damage to test specimens was also observed during impact tests. Main findings of the study are listed below.

- Acceleration values were measured by accelerometers at two symmetrical points of the specimens. It was observed that acceleration values were affected by the change in joint types and also by energy levels applied. Greater accelerations were obtained on test specimens that were equipped with the joint type 2 in which 10 bolts were used. On the other hand, acceleration values decreased from the first drop to the failure drop for all test specimens. The biggest difference between the first drops and failure drops were registered at maximum accelerations of the test specimen S2-A.
- Displacement values were measured by LVDT that was placed under the midpoint of test specimens. Maximum displacements were measured at failure drop of all test specimens. The change in impact energy due to the change in drop height affected displacement values. Displacement values were also affected by joint types. It was observed that measured values decreased when the joint region of test specimens became more rigid. While maximum displacements were obtained at test specimens with joint type 1, minimum values were measured at test specimens equipped with joint type 2. According to specimen displacement results, the ratio of the first drop displacement to the failure drop displacement ranged between 29.38% and 39.06%.
- Impact load values were determined by the dynamic load cell for each drop of steel hammer. Maximum impact loads were registered for the first drop of hammer. The values decreased as the test progressed. Besides, bigger impact

load values were measured when the impact energy applied on test specimens was increased. The maximum impact load was obtained at test specimen S2-B which was equipped with joint type 2 and tested for the 1250 mm drop height.

- Load-displacement curves were formed by the combination of impact load and displacement values for the same time interval. In this way, energy capacities of test specimens were investigated by considering the joint type of test specimens. While the difference between energy capacity values of the specimens tested at the 1000 mm drop height is 29%, it is 20% for the specimens tested at the 1250 mm drop height. This means that the effect of joint type configurations decreased with an increase in impact energy.
- Drop durations and the total number of drops were determined by optic photocells for each drop movement of steel hammer. No significant changes in drop duration were observed at test specimens at the same energy level. Drop durations increased as the energy level on specimens became greater, which was expected. The total number of drops was determined when failure damage situation was observed. Test specimens reached failure situation when the drop height was increased to 1250 mm.
- Finally, it is suggested by the authors that numerical analysis may be an option to investigate the behaviour of test specimens under sudden impact loading. In this way, the workload in the laboratory would be reduced. However, accurate material models and experimental conditions must be defined in the software. In addition, it is recommended that test specimens having different connection types and material characteristics be tested under various energy levels in future studies.

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