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Journal of Engineering Science and Technology
Vol. 15, No. 6 (2020) 3649 - 3660

SHEAR PERFORMANCE OF BEAM-COLUMN JOINTS SUBJECTED TO HIGH LOADING RATES

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Abstract

High loading rates may produce in structural frames due to some actions, such as explosions or debris impact. The response of structural members to such abnormal loadings should be investigated to provide comprehensive knowledge of their capability to resist impulsive forces. The beam-column joint is considered one of the most important structural components that significantly control the robustness and integrity of a structural frame. Hence, in the current study, eight full-scale specimens of two types of beam-column joints were tested under dynamic impact load to study their response to high rate load. These two types of joints were fin-plate and single angle-cleat joints. The tests were carried out using a drop hammer to apply an impact load on the specimens from different heights with different preloading conditions. The single angle-cleat joints exhibited a better response to dynamic loads with different impact height and preloading conditions than fin-plate joints in terms of resistance and ductility. Bolt shear failure was the dominant failure mode of the two types of the joints selected.

Keywords: beam-column, connections, high rates, impact load, joints.

1. Introduction

The past decade witnessed noticeable consideration on investigating the dynamic behaviour of beam-column joints such as impact and blast, which may be caused by different reasons such as, terrorist incident, construction faulty and debris or vehicle impact. The guidelines in the design codes were provided assuming static loading conditions with limited considerations to dynamic effects. However, studying the dynamic resistance of such joints is valuable to ensure the robustness and integrity of a structural steel frame, which in turn minimizes or prevents the probability of occurrence of progressive collapse. After the well-known collapse of World Trade Centre in the U.S., it was reported that joint resistance under combined impact-fire loads needs to be investigated to improve the performance of such a critical component in structural frames [1]. Therefore, it will be worthwhile to present experimental and theoretical studies, in which the dynamic behaviour of the connections can be understood.

As a response to this gap of knowledge, a series of studies were stared by investigating the response of various types of beams and columns under high loading rates [2-6]. The latter studies did not take into account the actual condition of connections to resist the applied impact load by assuming perfect support conditions. Besides, the structural frames with pinned or semi-rigid beam-column connections have less strength than the impacted column, which makes them more likely to fail before the columns. Al-Rifaie et al. [7] recognized this issue and a study was carried out to examine the response of beam-column joints with end-plate under transverse impact loading. Dynamic amplification factors up to 1.45 were proposed and similar deformation patterns under quasi-static and impact loading were observed.

Also, a similar study to the previous one was carried out but by connecting a concrete-filled steel tube column to a steel beam using end-plate joints [8]. It was found that increasing the end-plate thickness enhances the moment resistance of the joint with considerably reducing in its energy absorption. An experimental study was carried out by Grimsmo et al. [9] to investigate the behaviour of extended end-plate joints. The findings indicated that the extended end-plate joints became more ductile under impact load than static load. Nevertheless, Tyas et al. [10] showed that the partial depth end-plate connections became less ductile under impact test compared to that under the static one. Rahbari et al. [11] studied the response of double angle-cleat connections under loadings with different strain rates. The results indicated that the loading rate within the ranges studied has a relatively slight contribution on either the failure patterns or the strength and ductility of the joint investigated. The objectives of this paper are to predict the aerodynamic characteristics of projectiles using analytical and semi-empirical methods and study the effect of body shape; forebody and afterbody, on the aerodynamic characteristics of projectiles at supersonic speeds. For this purpose, five widely used projectile shapes are investigated. The geometry and full dimensions of these projectile shapes are shown in Fig. 1.

In addition to end-plate and web-cleat joints, fin-plate can be considered a preferred type of beam to column simple joints [12]. However, limited studies were carried out to investigate the dynamic response of such joints. Wang et al. [13] studied the behaviour of fin-plate joint subjected to a falling floor. It was found that reducing the bolt-to-bolt distance and the thickness of the fin-plate may accelerate the failure under lower impact loads. Experimental tests were carried out by Wang et al. [14] to investigate the response of different types of joints including fin-plate under falling debris. The findings showed that both ductility and load-carrying capacity of a joint contributed significantly to the energy absorption capability of joints. Static and dynamic response of fin-plate joints were investigated experimentally and numerically by Stoddart et al. [15]. The component method adopted by Eurocode to estimate the joint resistance was modified to consider the effect of high strain rate.

The current study is an extended part of the aforementioned studies conducted by Al-Rifaie et al. [7, 8, 16] and Grimsmo et al. [9]. In this paper, the structural response of two types of beam-column connections named fin-plate (FP) and single angle-cleat (SAC) connections with and without bolt preloading were investigated experimentally under transverse impact loads. The experimental work contained testing eight full-scale specimens using L-beam to column connection setup. Also, the effect of using different impact energies was investigated by hitting the specimens from different heights with a constant mass. The test setup was designed to apply a dynamic shear force and bending moment at the joints. Moreover, the tests were carried out considering the intention of using the experimental data in the validation process of finite element models.

2. Experimental Procedure

2.1. Test specimens

Figure 1 indicates the assembly of the L-beam to column test specimen. The size of column and beam were 152×152×37 (H-section) and 305×127×37 (I-section), respectively. Figure 2 shows the two types of joints investigated, i.e., the fin-plate (FP) and the single angle cleat (SAC). The practical consideration suggested by Eurocode 3 was considered in both types [1]. For FP joints, a 10 mm thick plate with 260 mm length was welded to the top flange of the column by 8 mm fillet weld then connected to the beam by three 16 mm high strength bolts with the grade 8.8. Whilst, for SAC joints, an angle of 80×80×10 mm thick and 260 mm length was connected by three high strength bolts to the column and another three bolts to the beam. The matrix of the specimens is shown in Table 1.

Table 1. Matrix of the specimen.

Specimen*	Type of joint	Height (m)	Pre-tensioning
FPN1	Fin-plate	0.57	Non
FPP	Fin-plate	0.57	Pre
FPN2	Fin-plate	1.15	Non
FPN3	Fin-plate	2.3	Non
SACN1	Single angle cleat	0.57	Non
SACP	Single angle cleat	0.57	Pre
SACN2	Single angle cleat	1.15	Non
SACN3	Single angle cleat	2.3	Non

*FP: Fin-Plate, P: Pre-tensioned, N: Non pre-tensioned SAC: Single Angle Plate, No number, 1, 2, and 3 for height of 0.57, 0.57, 1.15, and 2.3 m.

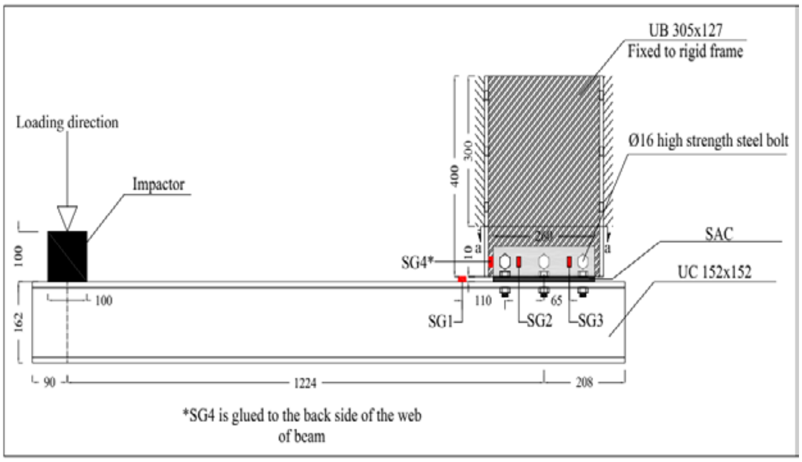


Fig. 1. Full test specimen used in the current study (all dimensions in mm).

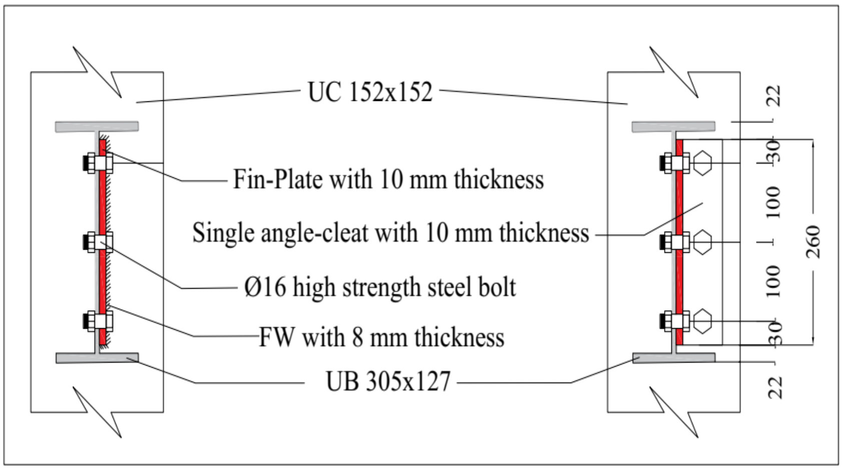


Fig. 2. Types of joints being investigated in the current study (Section-a-a in Fig. 1), (all dimensions in mm).

2.2. Material properties

Standard uniaxial tensile tests were carried out for all steel profiles and high strength bolts involved in the test specimens [17]. For accuracy purposes, the tests of each sample were repeated three times and excellent correlation amongst the replicated tests was obtained. Also, the coupons were taken from the flange and web of both the column and beam to be tested separately as their properties may be varied. The stress-strain traces of the web and flange of the profiles mentioned above showed an excellent correlation. Thus, the results from both the flanges were selected to represent the stress-strain traces of both beams and columns. The engineering stress-strain traces were acquired for all materials of the test specimens under quasi-static load except those of washers and nuts.

Figure 3 displays the stress-strain traces of the profiles used in the current study. It should be mentioned that such stress-strain traces did not represent the dynamic behaviour of the material used as it is a static test. However, they can be used to predict the dynamic behaviour of such materials especially with the unavailability of the equipment required for dynamic tests.

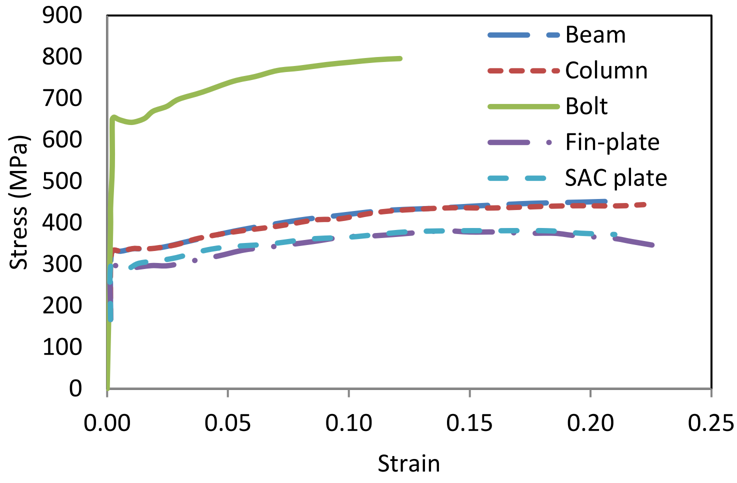


Fig. 3. Stress-strain traces of the steel profiles used in the current study.

2.3. Test set-up and instrumentation

Figure 4 shows the test setup containing the stiff frame, test specimen, and instrumentations. A stiff frame was used to support test specimens. The frame was designed and fabricated at the University of Liverpool and its rigidity to support the applied dynamic loading was also examined then approved [7]. The joints prepared were tested under a transverse impact load using a drop hammer with a maximum energy capacity of 107.5 kg × 2.9 m.

To carry out the impact test, the beam of each specimen was connected first to the stiff frame by 12 M16 high strength bolts. Then a flat impactor with a mass of 107.5 kg and a surface area of 100×100 mm was released from different heights (0.57 m, 1.15 m, and 2.3 m) to strike the free end of the column generating a combined dynamic tensile force and bending moment on the joint. A Laser Doppler Velocimeter (LDV) device was employed to obtain the velocity time history of the impactor during the impact loading event. The impact force was evaluated by multiplying the constant impactor mass by the acceleration, and the latter was determined from the numerical differentiation of the measured velocity time history. This technique was used in different impact studies and accurate impact force prediction was obtained [18].

The displacement time history of the impactor was captured using a high-speed camera (HSC). A licensed software named ProAnalyist motion analysis was used to obtain the displacement time history traces from the frames captured by the camera. Furthermore, the strain time history traces were captured at four locations on each specimen using multipurpose strain gauges as shown in Fig. 1. Such strain-time history traces will assist to investigate the strain rate in the selected locations. Frictional lock between two bolted plates can be enhanced by applying additional torque during bolt tightening process. This will improve the tensile and shear strength of the bolted joints. However, two samples were preloaded and then tested to investigate their response to impact load. The preloading process of joints was carried out by applying a torque of 200 N.cm on the nuts of each bolt using an appropriate torque wrench as specified by ISO 898-1 [19]. Additional information about test methodology can be found in reference [20].

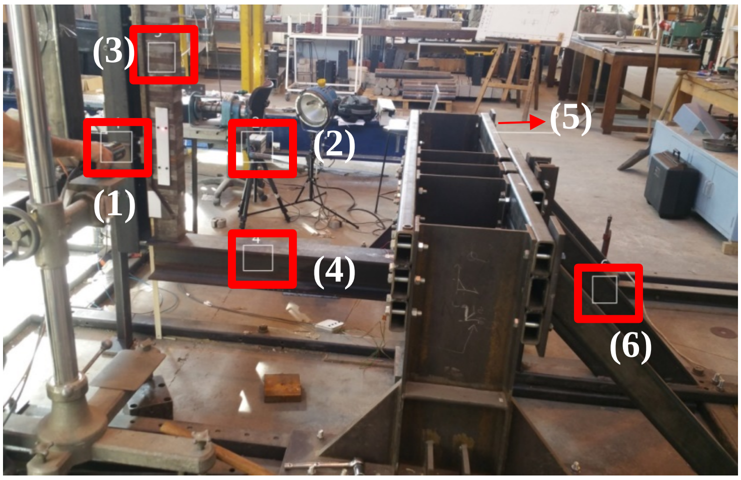


Fig. 4. Test setup, (1) LDV device (2) HSC (3) drop hammer (4) tested specimen (5) stiff frame and (6) bracers.

3. Test Results and Discussion

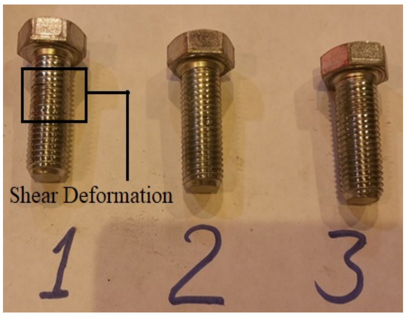
3.1. Failure modes

Large displacements have been observed, as expected, in the free end of the specimens t. This could be attributed to the low moment resistance of the joints tested. The results from all tests demonstrated three different modes of failure. The first mode that joints experienced was the shear failure of the bolts that connect the beam to the joints. The second failure mode occurred only in the SAC joint, which was the plastic bending of the angle flange. The third one represented by the bearing failure of the holes of both beam and plate of both joints investigated.

For non-preloaded joints impacted from a height of 0.57 m, no of the failure modes mentioned above were observed except a little shear deformation in the first bolts of both joints, as indicated in Fig. 5(a). While this shear deformation was not observed in the preloaded joints impacted from a similar impact height. This indicates the contribution of preloading of bolts in enhancing joint strength. Samples impacted from a height of 1.15 m demonstrated shear failure of the first bolt for both joints corresponding to shear deformation of both the second and third bolts. Besides, bearing deformation was observed on the hole of the failed bolts for both joints studied as shown in Fig. 5(b). Moreover, the samples impacted from a height of 2.3 m experienced a higher deformation rate. Both the first and second bolts were broken, corresponding to higher bearing deformation of their beam holes underneath (see Fig. 5(c)). It can be said that similar deformation modes were obtained for both joints studied under different impact heights and preloading conditions except the bending of the SAC, shown in Fig. 5(d), which was not induced in FP joints. Such bending makes the SAC joint more preferred than the

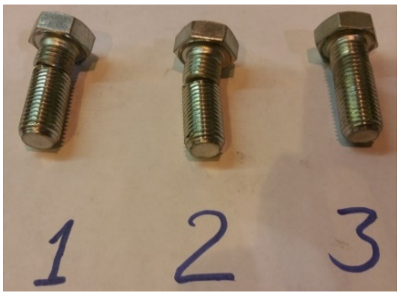
FP joint as it contributes to delay the sudden failure of the joint, leading to lower displacement and lower rotation compared with the FP joints. In other words, SAC joints seem to be more preferred than the FP joint to achieve the ductility and flexibility required for joints to resist extreme loading.

The fillet weld of FP joints can correspond to the bolts under tension in SAC joints. No deformation was observed in both of such components for preloading and impact height conditions investigated. It may be a good indication that the practical consideration that suggested 8 mm fillet weld with 10 mm fin-plate thickness in Eurocode 3 is safe and conservative against impact loads rather than static loads.

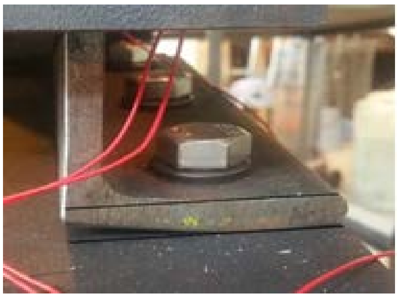


(a) Bolt deformation (SACN1).

(b) Bearing deformation (FPN2).



(c) Bolt deformation (SACN1).



(d) Bending deformation (SACN3).

Fig. 5. Failure modes obtained for FP and SAC joints.

3.2. Force-time history

The force-time histories for the specimens are presented in Fig. 6(a) to Fig. 6(d). In general, increasing the impact height leads to rising the impact force induced in the free end of the column stroke for both joints investigated. The force-time traces show that the impact force jump from zero up to maximum peak force within less than 4.5 milliseconds, and then it falls to zero due to the contact missing between the impactor and the specimen surface, indicating the elastic collision between the impactor and column stroke. Afterward, the second peak force starts to develop, which in turn decreases to zero due to the same reason above but with more time than the first peak. The second peak obtained in the load time trace was lower than the first peak because the change in impactor velocity was smaller. For comparison purposes, force-time histories for both joints were placed on a single graph for different pre-loading and height conditions. Figure 6(a) shows the comparison between the samples with pre-tensioned FP and SAC joints. It can be seen that with 0.57 m impact height, the specimen with the SAC joint exhibited higher impact peak force than the one with FP joint by 9.1%.

A comparison of both preloaded joints impacted from 0.57 m height was also presented in Fig. 6(b). It can be noted that with the same impact height, the impact force reached 25.2 kN when SAC joint used, whilst the specimen with FP joint resists with force equal to 23.5 kN. The higher forces induced in the preloaded joints reflect its contribution to enhancing the resistance of both types of joint investigated. By increasing the impact height from 0.57 to 2.3 m, the force increased from 25.2 kN to 118.2 kN for the specimens with a SAC joint, while it increases from 23.5 to 106.4 kN for the ones with FP joint as shown in Fig. 6(b) to Fig. 6(d). Based on the force-time history results, it is clear that SAC joints exhibited higher resistance than the FP ones. This could be attributed to the more flexible nature of SAC joints that the flange of its angle offered, which is missing in FP joints. Four resistance components can be noticed in the SAC joints represented by bolts in shear, bolts in tension, bearing resistance of bolt holes in both beam and plate in addition to the flexible angle flange. Whilst only bolts in shear and bearing resistance of holes can be recognized in fin-plate joints. However, more impact resistance was obtained from SAC joints than those with FP joints.

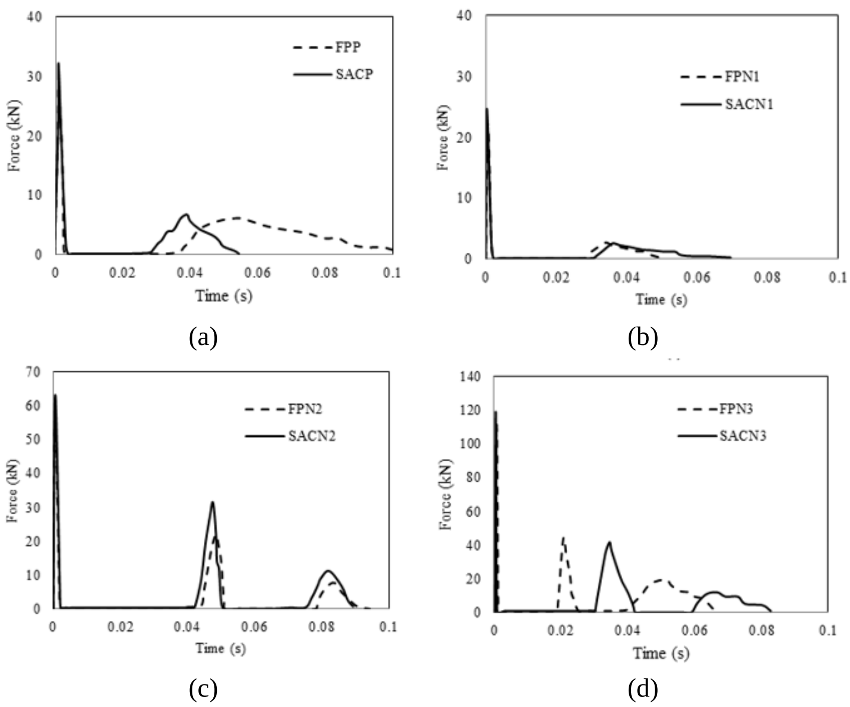


Fig. 6. Force-time histories for the specimens.

3.3. Displacement-time history

Generally, the displacement of each specimen starts to rise, corresponding to the movement of the impactor and column stroke downward until reaching its maximum value. Then, the column and impactor begin together to move up showing a decent from the maximum displacement point in the displacement time curves. As the impactor starts to lose its contact with the stroked column during the upward movement, the data were stopped to be collected and were not shown such curves. Again, the results prove that the SAC joint is preferred as it exhibited higher deformation resistance. The pre-tensioned FP joints impacted from a height of 0.57 m experienced higher deformation than the one with SAC type as shown in Fig. 7(a). As expected, increasing the impact height or impact energy causes a higher displacement. The recorded displacements of non-preloaded samples with FP and SAC joints were 120 and 111 mm, respectively when the impactor hits the columns from a height of 0.57 m as can be seen in Fig. 7(b). With almost the same duration of the impact event, the displacement increases with raising the impact height regardless of the type of connection. However, the beam-column connection using the SAC shows 111, 178 and 219 mm with an impact height of 0.57, 1.15 and 2.3 m, respectively. While deformation of specimens with FP joint were 120, 202, 229 mm under the same impact conditions as shown in Figs. 7(b) to Fig. 7(d).

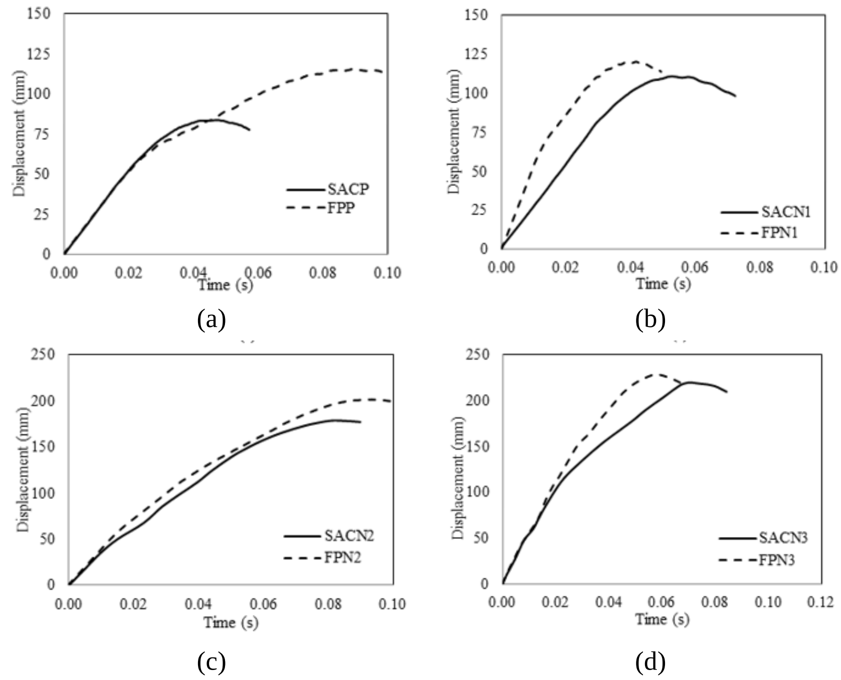


Fig. 7. Displacement-time histories for the specimens.

3.4. Strain-time history

As mentioned in Section 2.3, strain-time history in different locations on the specimens was measured to investigate the strain rate limits during the impact event. The locations specified were selected as they represented the critical points that experienced higher deformation and strain rate. This was obtained by a preliminary finite element (FE) investigation of one sample. It's supposed to place two strain gauges directly underneath each bolt hole, as obtained from FE results. However, it was impractical to place such gauges in those locations because they will be damaged during the tightening of nuts. Thus, they were moved about 3 cm down to avoid their damage. The other two locations on beam and columns were selected as per FE results. The results did not show a high strain rate in the selected locations considering the high strain rate produced for an impact event. This may belong to the practical issues in which strain gauges cannot be placed where the higher strain produced such as locations near holes (where the bearing failure occurred) or in the bolts (where the shear failure occurred). Figure 8 shows the strain time history of the worst-case tested that experienced the highest displacement, which was FP specimen impacted from a height of 2.3 m (specimen FPN3). In general, it can be concluded that the strain in the four locations selected did not exceed its elastic limit. Also, it can be seen that higher strain was obtained in the gauges located on the fin-plate if compared with other parts (beam and column) of the specimen selected. Strain rate represents the slope of the strain time history relationship at infinite time intervals. Based on this fact, it is clear from Fig. 8 that a higher strain rate was produced in the first half of the impact event compared with the last half. This observation can be noted in SG2 as the strain reaches around 2250 µm within 10 ms. In another word, the strain rate was around 0.225 assuming a straight-line relationship during this time interval, which is a small value considering the high strain rate might be induced during an impact event. This is because SG2 was not located where higher deformation developed. Afterwards, the strain rate reduced obviously and the slope of the curve seems to be less.

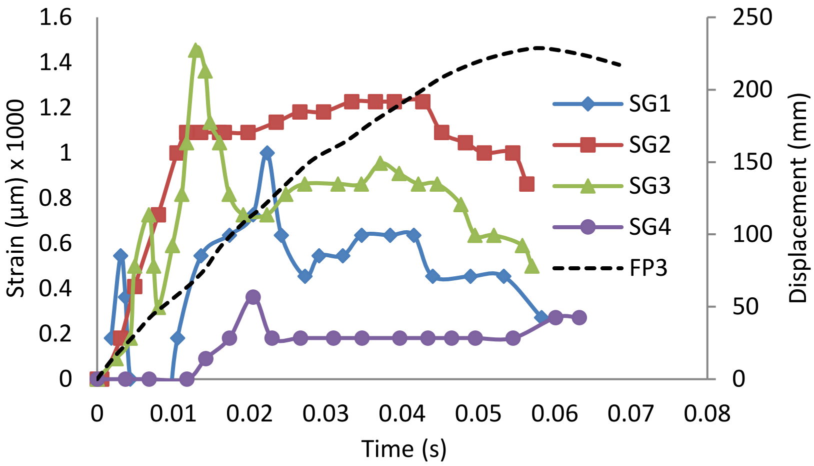


Fig. 8. Strain and displacement time history of specimen FPN3.

4. Conclusions

This study was conducted to investigate the transverse impact response of two simple beam-column joints named fin-plate and single angle cleat joints. The literature showed that the studies available were limited, and more research efforts are required. Eight full-scale beam-column joints with different impact energies and preloading conditions were tested under transverse impact. The test specimens were impacted by a mass of 107.5 kg with impact height that ranged between 0.57 and 2.3 m. Finite element analysis can be developed and verified against the test data obtained to examine more parameters related to the dynamic response of joints investigated. The following conclusions can be drawn:

- The impact event of the specimens included two or three stages. The specimens impacted with the lower velocity experienced two stages starting with a peak force during a short time and ending with a steady force with longer time. Whilst only three peak forces were observed in specimens impacted with higher velocities. A gradual decrease in the three peak forces was noticed during the impact event corresponding to an increase in the time interval of each peak force.
- The experimental results show that the SAC joints behave in a better manner than fin-plate joints under dynamic loading as higher impact forces and lower joint rotations were produced in the former joint. SAC joints seem to be slightly stiffer and more ductile than fin-plate joints under fast loading conditions.
- Also, the critical failure mode of both joints was similar, represented by the shear failure of bolts.
- The effect of bolt pre-loading seems to have negligible effect on the maximum displacement of FP joints. However, the maximum displacement of pre-loaded SAC joints considerably affected to be 77% of the non-pre-loaded one.

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