

Full paper

Experimental investigations on the reusability of bearing resistant joints made of High Strength Steel

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Abstract

The reusability of structural elements is considered as one of the most promising strategies to reach the carbon neutrality of the civil engineering sector in 2050, as recommended in the Paris agreement. The structural joints are identified as key elements to promote the demountability and reusability of structures. However, beyond regulatory barriers to reuse, some mechanical phenomena require to be mastered, such as the bolt hole deformation in bearing-type connections and, in particular, the development of remanent plastic deformation, which is a key parameter to be mastered to ensure an easy and safe reuse of connecting elements in future applications.

In this context, the present paper reports on the results of an experimental campaign, in which a serie of bearing tests were conducted on plates made of S355 and S460 steel grades with non-prestressed bolts. The objectives of these tests are triple: (i) to assess the bearing deformation on the bolt hole for plates made of S460; (ii) to compare the bearing behaviour between normal steel grades (S355) and high-strength steel (S460) and (iii) to derive a preliminary criterion to limit the bolt hole deformation.

Keywords

Bearing deformation, Bolted connection, EN1993-1-8, Reusability, High-strength-steel

1 Introduction

The steel industry is under increasing pressure to reduce CO₂ emissions, as it remains one of the largest contributors to global greenhouse gases. In line with the European Green Deal objectives [1] for climate neutrality by 2050, several strategies can be highlighted : optimisation of the material distribution, designing with high-strength steel (HSS) to minimize cross-sectional dimensions, and promoting the reuse of structural elements recovered from already existing buildings. While these approaches could offer significant potential for greater sustainability and reusability, the latter possible solution is constrained by current European design standards which are not addressing yet this solution. In particular, bolt hole deformation in

bearing-type connections made of high strength steel represents a key parameter for ensuring the safe reuse of connecting elements. This phenomenon can be met for instance in the web of a beam that is connected through fin plate joint to the supporting element. As the load is transferred mainly through bearing actions, and as this component exhibits a nonlinear behaviour associated to yielding at an early stage of loading, recommendations are mandatory to ensure the potential of reusability of the beam, limiting the plastic deformation around the bolt hole.

The benefits of HSS elements are well established in the literature ([2]-[5]). In particular, this material enables significant reductions in the cross-section dimensions of the constitutive elements of a structure, leading to an overall weight decrease, while preserving the same load-bearing

capacity, as elements made of conventional steel grades could be reached. In addition, in the past years, European research projects ([6]-[7]) have investigated the structural behaviour of high-strength steel (HSS) elements, resulting in significant progress in design recommendations.

Regarding the bearing behaviour of joints, various research were previously carried out on double shear joints with one bolt or multiple bolts. In particular, Moze et al. [9] provide a complete study of bearing stress in single bolt connections with mechanical connector subjected to double shear. Lyu et al. [10] conducted 30 multi-bolts bearing tests on plates made of HSS with Q550D steel grade to evaluate their ductility and their resistance. Draganić et al. [11] performed bearing tests on plates made of S235 steel grade with bolt loaded in single shear, resulting in bolt pull-through failure mode.

This paper presents the outcomes of eight bearing experimental tests conducted on plates fabricated from both conventional steel (S355) and high-strength steel (S460), considering two different plate thicknesses. Specifically, particular attention was placed on the bolt hole deformation and the capacity of reassembling the plates. In half of the tests, once the serviceability limit load was reached, the plates were disconnected and subsequently reassembled in order to assess their remountability under realistic conditions of structural reusability. The experimental results were then compared with the resistance provisions outlined in the recently published EN1993-1-8:2024 [12].

This research takes place in the framework of the RFCS European project Connect4C, aiming at developing recommendations for the reusability and the adaptability of steel joints. It involves different European universities, office design and private companies. Outcomes of the project which are already published can be found in [13]-[14].

2 Experimental test campaign

2.1 Experimental sample

As previously stated, eight experimental double shear bearing tests were performed, considering two different steel grades (S355 and S460), two plate thicknesses ($t_p = 6$ mm and 12 mm), and two loading sequences (ULS and SLS-ULS) which is the specificity of this research. Indeed, for the specimen loaded based on the SLS-ULS sequence, for an applied load equal to the serviceability limit state (SLS) resistance, the specimen was unloaded. This allows the assessment of the plastic deformation in the vicinity of the bolt hole, due to the bearing action effect. Then, the plates were reassembled and placed again in the test machine, and the facility to rebuilt the system was evaluated. Each test was named as follow " $f_y - t_p - \text{sequence}$ "; Table 1 summarises the eight tested specimens.

The geometry of the internal tested plates is illustrated in Figure 1(a), while the geometrical properties of the external lap plates are presented in Figure 1(b). For the internal plates, the principal dimensions, i.e. the length (450 mm), the width (140 mm), and the bolt hole edge distances e_1 (40 mm) and e_2 (70 mm), were kept constant across all tests to facilitate direct comparison of the results. The dimensions of the lap plates, made of S460 steel grade, except for the bolt hole diameter, are the same for the eight

tests. The size of the bolt is either M24 10.9 or M27 10.9, for the thinner and the thicker plate, respectively. The bolts are partially threaded with the specificity that the tested internal plates are in contact with the unthreaded portion.

Table 1 Bearing test specimens details

f_y [MPa]	t_p [mm]	Loading sequence	d_o [mm]	$F_{b,Rk}$ [kN]
355	6	ULS	26	108.55
355	6	SLS-ULS	26	108.55
355	12	ULS	30	211.68
355	12	SLS-ULS	30	211.68
460	6	ULS	26	107.67
460	6	SLS-ULS	26	107.67
460	12	ULS	30	209.95
460	12	SLS-ULS	30	209.95

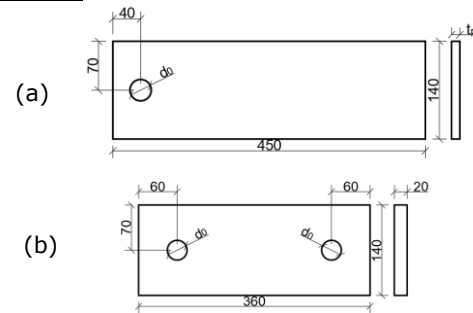


Figure 1 Geometrical properties (a) internal tested plate and (b) external lap plate

The bearing characteristic resistance of the internal plates, reported in the last column in Table 1, is computed based on the new version of the normative document EN1993-1-8:2024 (Table 5.9 in Section 5.3), taking into account the nominal geometrical and mechanical steel properties. According to the steel grades, the material parameter k_m is taken as equal to 1.0 (S355) or 0.9 (S460), as recommended. This material coefficient is the reason for which the resistance of the higher steel grades plates are just lower than the one with the conventional steel grade, even if the ultimate stress resistance is higher for the S460 steel grade.

2.2 Design of the experimental test set-up

The test configuration, presented in Figure 2, was designed to ensure that the governing failure mode corresponds to the bearing resistance of the internal plate, rather than alternative failure component such as bolt in shear or plate in tension. This design was carried out by applying the provisions given in EN1993-1-1:2022 [15] for the plate in tension component (gross ($N_{t,Rk}$) and net ($N_{u,Rk}$) sections) and EN1993-1-8:2024 for the bolt in shear ($F_{V,Rk}$) and block tearing resistance ($V_{eff,Rk}$). These are provided in Table 2 for the internal plates only, as the external lap plates are larger and thicker, and therefore not critical for the tested lap joints.

Table 2 Test set-up design

Specimens	$F_{b,Rk}$ [kN]	$N_{t,Rk}$ [kN]	$N_{u,Rk}$ [kN]	$V_{eff,Rk}$ [kN]	$F_{V,Rk}$ [kN]
355-6	108.55	298.2	301.64	384.35	542.87
355-12	211.68	596.4	582.12	745.18	687.07
460-6	107.67	386.4	332.42	433.10	542.87
460-12	209.95	772.8	641.52	840.28	687.07

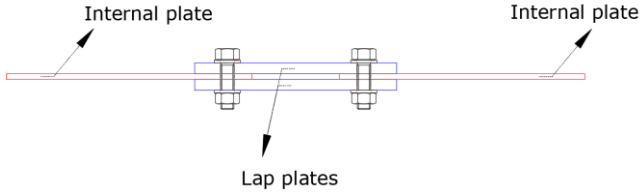


Figure 2 Test configuration

The ratio between the weakest component (excluding the bearing one) and the bearing resistance of the internal plate is equal to 2.75 for all S355 specimens and 3.08 for the S460 specimens. These ratios provide a sufficient safety margin, ensuring that the bearing resistance of the plate is reached prior to the activation of any other failure modes, even in case of significant tested plate material overstrength.

2.3 Instrumentation

In order to monitor the bolt hole deformation, one Linear Variable Differential Transformer (LVDT) was positioned above each bolt hole between the lap plates and the internal plates at the middle of the plate width, as shown in Figure 3. This allows the measurements of the relative displacement between the plates throughout the entire duration of the experimental test.

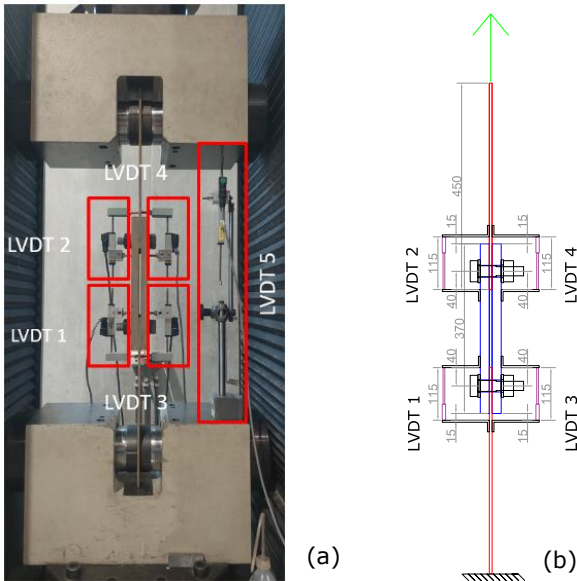


Figure 3 Machine testing set-up (a) picture and (b) exact position of the LVDTs

In addition, all internal plates were laser-engraved with a square mesh of 10 mm side length, centred on the bolt hole. This allows for a visual evaluation of the plate deformation under bearing actions. Finally, during the experimental test, the applied load was recording as well as the displacement of the machine through the fifth LVDT (Figure 3(a)).

2.4 Testing protocols

The entire experimental test campaign was performed using a electro-mechanical testing machine with a capacity of 600 kN, by controlling the applied displacement, with a

speed rate included between 0.2 mm/sec and 2.5 mm/sec, according the real-time response of the specimen.

Overall, the testing protocol is quite comparable between the two loading scenarios. Prior to the beginning of the test, both bolts were preloaded at 5% from the full preload recommended value, by applying a torque moment. Then, for a given load intensity equal to $0.4 \cdot F_{b,Rk}$ and $0.4 \cdot F_{b,Rk}/1.4$, for the ULS and SLS-ULS loading scenario, respectively, the specimen is partially unloaded to ensure that all offset are removed from the system. Subsequently, for the ULS loading sequence, the load was increased until failure. However, for the SLS-ULS loading sequence, the applied load increased up to an intensity equal to $F_{b,Rk}/1.4$, defined as the SLS bearing resistance $F_{b,Rk,SLS}$. Then, the specimen was fully unloaded and all the constitutive parts were removed from the testing machine, to measure the bolt hole deformation. Afterwards, the plates were placed again in the testing machine, with new bolts, and the test restarted following the ULS loading sequence protocol.

Prior to the beginning of the test, the upper bolt was placed in direct contact with the bearing bolt hole side, avoiding the slipping of the plates at this level during the test, while the lower bolt was positioned at the middle of the bolt hole.

3 Experimental results

3.1 Tensile coupon test results

The materials of the different specimen plates were characterized through tensile tests. For each steel grade and thickness, dog-bone specimens (see Figure 4) were extracted from the steel batch, in the rolling direction. The obtained engineering stress-strain curves are provided in Figure 4, and the main mechanical properties are reported in Table 3.

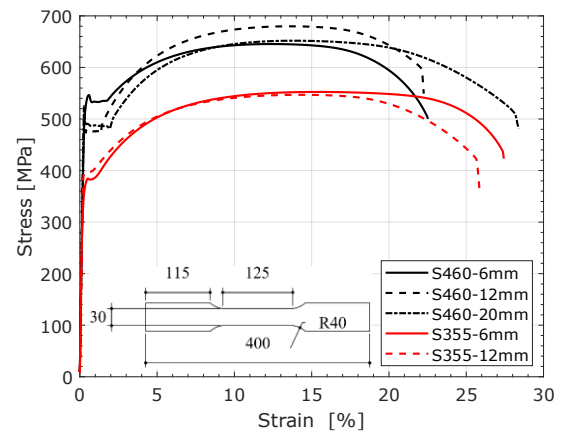


Figure 4 Engineering stress-strain curves

The material properties of the steel plates were compared against the ductility requirements specified in EN1993-1-1:2022 regarding the f_u/f_y ratio that should be higher than 1.10 for an elastic global analysis and the elongation at failure A that should be equal or higher than 15%. The tested steels satisfied these requirements. As expected, for the same thickness, the elongation is higher for S355 steel grade than for the S460 one.

Table 3 Mechanical steel properties

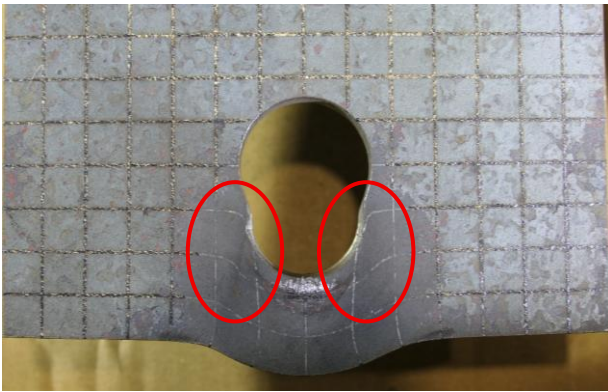
Coupon	R_{eH} [MPa]	$R_{p0.2}$ [MPa]	R_m [MPa]	A [%]	E [MPa]
S460-6	546.40	536.84	645.43	22.3	215,374
S460-12	496.28	478.37	679.80	21.9	186,958
S460-20	525.22	490.55	651.84	28.1	201,485
S355-6	-	372.94	552.52	27.2	221,815
S355-12	-	395.52	546.91	25.6	163,947

3.2 Plate in bearing test results

All the eight experimental bearing tests reached the tear-out resistance (see Figure 5 for *S460-12-ULS* specimen). The ultimate applied force F_u and its associated displacement u_u are provided in Table 4. It should be mentioned that the reported displacement corresponds the net deformation value, meaning that the initial slipping between the plate was removed. The penultimate column details in which internal plate side (up or down) the failure appeared.

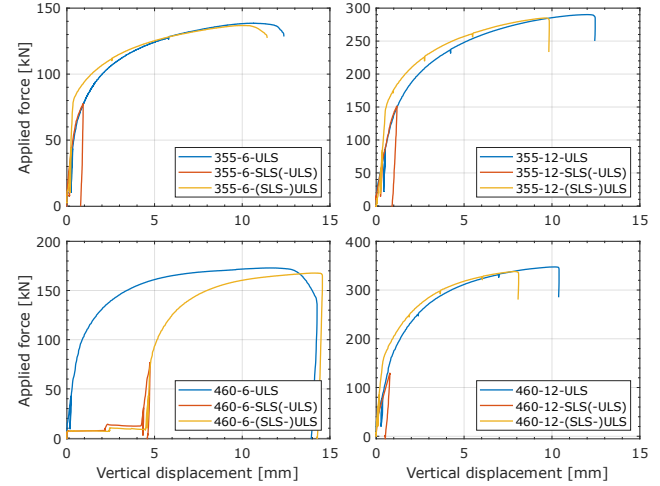
Table 4 Experimental test results

Specimen	F_u [kN]	U_u [mm]	Failure plate	$F_u/F_{b,Rk}$ [kN]
355-6-ULS	138.50	10.52	Up	1.14
355-6-SLS+ULS	136.80	10.06	Up	1.13
355-12-ULS	290.50	13.47	Down	1.22
355-12-SLS+ULS	285.10	11.62	Down	1.20
460-6-ULS	172.93	11.54	Up	1.33
460-6-SLS+ULS	167.73	10.77	Down	1.27
460-12-ULS	337.99	11.01	Down	1.24
460-12-SLS+ULS	347.41	9.41	Down	1.28

**Figure 5** *S460-12-ULS* cracked specimen

The experimental results highlight that, as expected, the bearing resistance increases with both plate thickness and steel grade. The ratio between the experimental ultimate resistance and the characteristic resistance computed in accordance with the provisions in EN1993-1-8:2024 considering the actual geometrical and mechanical properties, $F_u/F_{b,Rk}$, demonstrates that the experimental resistance is always higher than the analytical predictions. This ratio is higher for the HSS plates, with a mean value of 1.28, compared to 1.17 for the S355 specimens. Furthermore, as the failure mechanism is influenced by the steel micro-structure, fracture occurred either in the lower or in the upper internal plate sides. The curves linking the applied load vs the relative displacement recorded by LVDT 2 (see

Figure 3) are provided in Figure 6. This LVDT was selected in order to avoid the slip displacement phase appearing in the lower internal plate. However, for the *460-6-SLS-ULS* specimen, a small compression was applied on the plates before the beginning of the test so that the shank of the bolt was in contact with the opposite bearing bolt hole side. This procedure allowed the comparison of plastic deformation between the SLS and ULS phases from an identical starting point.

**Figure 6** Load vs. vertical displacement curves

The ultimate deformation is always lower for the SLS+ULS tests compared to the ULS ones. This behaviour can be attributed to the initial plastic deformation induced during the first SLS loading phase. For the S355 steel grade, the elongation is higher for the thicker plate, while the opposite can be observed for the S460 steel grade. However, for a 6 mm thickness, the ultimate elongation is higher for S460 plates than for S355 plates while the opposite is observed for the 12 mm thickness plate. These findings reveal a non-negligible discrepancy in the ultimate elongation of the specimens, as no consistent correlation can be established across the different steel grades and thicknesses.

Regardless of the loading sequence, the overall shape of the load vs. vertical displacement curve remains similar across all tests. This characteristic shape is consistent with observations reported in other experimental studies available in the literature (see [16]). The graphs reveal an excellent correspondence between the ULS loading sequence and the SLS phase of the SLS+ULS sequence, thereby confirming the reliability of the experimental results. Moreover, for the SLS+ULS loading sequence, the initial slope of the ULS loading curve is parallel to the slope of the unloading curve of the SLS part as expected. In addition, during the ULS loading of the SLS+ULS sequence, once the applied load intensity reached the SLS resistance, the curve behaviour converged with that observed under pure ULS loading conditions.

Between the SLS and the ULS loading sequences of the SLS+ULS tests, the bolt hole deformation was measured in two main directions (0° and 90°, i.e. parallel and perpendicular to the loading direction, respectively) with a caliper to assess its bearing plastic deformation. Results for the four specimens are provided in Table 5, with the

corresponding initial bolt hole diameter and the relative elongation $(d_{0,SLS,0} - d_0)/d_0$.

Table 5 Bolt hole deformation corresponding to the SLS resistance, in [mm]

Specimens		d_0	$d_{0,SLS,0}$		$d_{0,SLS,90}$	
355-6	Up	25.85	26.59	2,9%	25.99	0,5%
	Down	25.90	26.35	1,7%	25.91	0,0%
355-12	Up	30.05	30.76	2,4%	30.07	0,1%
	Down	29.92	30.61	2,3%	29.93	0,0%
460-6	Up	26.03	26.38	1,3%	26.14	0,4%
	Down	26.03	26.38	1,3%	26.14	0,4%
460-12	Up	29.85	30.03	0,6%	30.01	0,5%
	Down	29.84	30.03	0,6%	30.03	0,6%

Comparing the initial and the deformed bolt hole diameters, only limited deformations were observed parallel to the loading direction, while deformation in the perpendicular direction remained negligible. Furthermore, between the two loading steps, no difficulties were encountered in reassembling the test set-up with the previously tested plates. These observations provide encouraging evidence for the feasibility of reusing such structural components providing that the load criterion is respected.

In the *S460-6* graph, the plastic deformation developed during the SLS loading can be clearly observed during the ULS one, as there is a horizontal offset between the two curves, that corresponds to the remanent deformation around the bolt hole. The relative difference is equal to 0.25 mm, comparing this value to the measured deformation reported in Table 5, there is a good correspondence.

For each tests, the slope of the straight line associated to the unloading-reloading sequence corresponds to the stiffness of the lap joint and can be computed, as provided in Table 6. It should be mentioned that during the ULS sequence of the SLS+ULS scenario, the unloading-loading occurred for a load intensity lower than the SLS resistance value. In addition, the unload-reload sequence was not performed for the *460-12 SLS* specimen due to technical issues.

Table 6 Unload-reload stiffness comparisons, in [kN/mm]

	ULS	SLS-(ULS)	(SLS)-ULS
355-6	340.5	2043.4	1030.4
355-12	708.5	586.6	550.5
460-6	432.1	742.5	392.4
460-12	696.1	-	866.6

From the results, it can be observed that the computed stiffness is significantly varying from one test to another for a same plate configuration. This can be explained by a high sensitivity of this value to the local yielding phenomena developing at the interface between the bolt and the hole perimeter. Also, the fact that the specimens are very stiff, meaning that the recorded displacements during the unloading-reloading sequence are very small (and close to the resolution of the sensors) induces a high influence of the selected points on the unloading-reloading branch of the curves on the computed stiffness.

For the ULS loading sequence, the stiffness increases with the thickness as expected. Furthermore, during the ULS

phase of the SLS+ULS loading sequence, the measured stiffness is systematically lower than that recorded during the initial SLS loading. This reduction can be attributed to the prior plastic deformation introduced during the SLS phase, which affects the structural response during subsequent loading.

For the connection where bearing deformation should be limited, EN1993-1-8:2024 introduces a reduced adjustment factor for bearing resistance, $\alpha_{b,red}$, that constrains bolt hole elongation to $d/6$. The corresponding characteristic reduced bearing resistance, $F_{b,Rk,red}$, for each type of specimen is presented in Table 7, with both the classical bearing resistance and the SLS-derived resistance from this research.

Table 7 Reduced bearing resistance

Specimens	$F_{b,Rk}$ [kN]	$F_{b,Rk,Red}$ [kN]	U_{Red} [mm]	$F_{b,Rk,SLS}$ [kN]
355-6	108.55	86.84	1.26	77.54
355-12	211.68	169.34	1.56	151.2
460-6	107.67	107.67	1.08	76.91
460-12	209.95	209.95	1.52	149.97

The ratio between the reduced bearing resistance and the SLS bearing capacity, $F_{b,Rk,Red}/F_{b,Rk,SLS}$, is equal to 1.12 and 1.4 for S355 and S460 steel grade plates, respectively. During the experimental test campaign, it has been demonstrated that for the SLS bearing resistance, the bolt hole deformation in the direction parallel to the applied load is limited. The elongation obtained experimentally at a load corresponding to the reduced bearing resistance, U_{red} , is provided in Table 7. Even if these values account for the bolt in shear deformation and the elastic axial elongation of the plates in addition to bolt hole deformation, these actual deformations remain below the $d/6$ threshold, equal to 4 mm and 4.5 mm, for 6 mm and 12 mm plate thicknesses, respectively. This indicates that the computation of the bearing resistance associated to a deformation limit equal to $d/6$ as proposed in EN1993-1-8:2024 is not in agreement with the experimental observations from the conducted test campaign. This would deserve additional investigations. However, it has been demonstrated through the performed tests that the demountability and the remountability is guaranteed for the considered $F_{b,Rk,SLS}$ without strongly affecting the global joint response.

4 Conclusions

This paper presents preliminary findings from an experimental test program performed on plate in bearing made of S355 and S460 steel grades in the framework of the CONNECT4C project aiming at developing and validating adaptable, demountable and reusable joint solutions.

In particular,

- Eight bearing tests were conducted on plates made with S355 and S460 steel grades with 6 mm and 12 mm thicknesses;
- The observed failure mode in all tests was consistent and corresponded to a tear-out failure mode;
- A specific loading sequence was applied to assess the bolt hole deformation for an intensity of the load equal to an assumed SLS loading;

- A perfect correlation in the global behaviour was found between both ULS and SLS+ULS loading sequence;
- Comparing the ultimate resistance with the recommendations from the normative document, it has been shown that the latter is always conservative;
- No difficulties were encountered after the SLS loading step, for the re-assembly of the constitutive plates;
- No significant influence of the initial SLS loading sequence on the global behaviour of the tested joints was observed;
- For an intensity of applied load equal to the SLS resistance, the measured bolt hole deformations parallel to the loading direction were limited (maximum 2.9%) and negligible in the perpendicular direction.

Further investigations will be conducted, primarily through numerical simulations based on the experimental test results, with the final objective of developing analytical recommendations to limit the bolt hole deformation and thereby facilitate the safe and easy reuse of structural steel elements.

Acknowledgement

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