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SPECIAL JOINTS FOR ALUMINUM EXTRUDED PROFILES: EXPERIMENTAL ASSESSMENT OF THE MECHANICAL RESPONSE

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Abstract

Special joint systems are obtained by means of mechanical fasteners located in semi-hollow parts of aluminum extruded shapes. These innovative joint typologies are very competitive with respect to conventional joining solutions thanks to the possibility of easy and rapid execution, optimization of parent material, treatments, and machining reduction. The fields of application of special joints are very wide from building and civil engineering to transportation and aerospace industry. Very little literature is available about the structural response of special joints, whereas main codes for aluminum structures only partially cover this topic and the design is allowed only by means appropriate and expensive experimental tests. For these reasons, the aluminum industry is very interested to enhance the knowledge about the structural behaviour of such joints. In order to overcome this lack of information, an experimental campaign aimed at assessing the structural response of two typologies of special joints, namely, "*bolt-channel*" and "*screw port*", has been carried out at the University "Federico II" of Naples. Different configurations, geometries, and loading conditions have been investigated for a total of 71 tests on joints.

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1. Introduction

The wide choice of cross-sectional shapes obtainable by means of extrusion process represents one of the main advantages for aluminum alloys structures. The extrusion process allows to customize the cross-section shapes with ribs, bulbs, slots in order to optimize the structural efficiency. These features can be also exploited to conceive the connections between the different parts of the structures in a more rational way. The achievable joining methods are various and they may or may not involve the use of fasteners. In general, such types of joints use extruded cross-sections with semi-hollow parts in which mechanical fasteners can be located. These systems are generally known as “special joints” or “non-conventional joints” for aluminum extrusions. Special joints represent a very competitive solution with respect to conventional joining systems, namely, bolted and welded connections, thanks to the possibility of easy and rapid execution, treatments, and machining reduction. The main advantage of using these joint typologies lies on the optimization of the parent material with a reduced need of additional joint elements, such as angles and gusset plates. These features entail a significant reduction in fabrication and execution costs.

Among the different special joint typologies, the most used systems are the *bolt-channel* and *screw port* joints. In *bolt-channel* joints, the bolt head or its nut is placed inside a track of an extruded section, whereas the screw port joints consist of an extruded slot in which a screw shank is located. These joints are commonly used in many structural applications under middle-low loads not only in building and civil engineering, but also in transportation industry. Typical applications in buildings are door and windows frames, photovoltaic support systems, staircases, shelves, and industrial furniture.

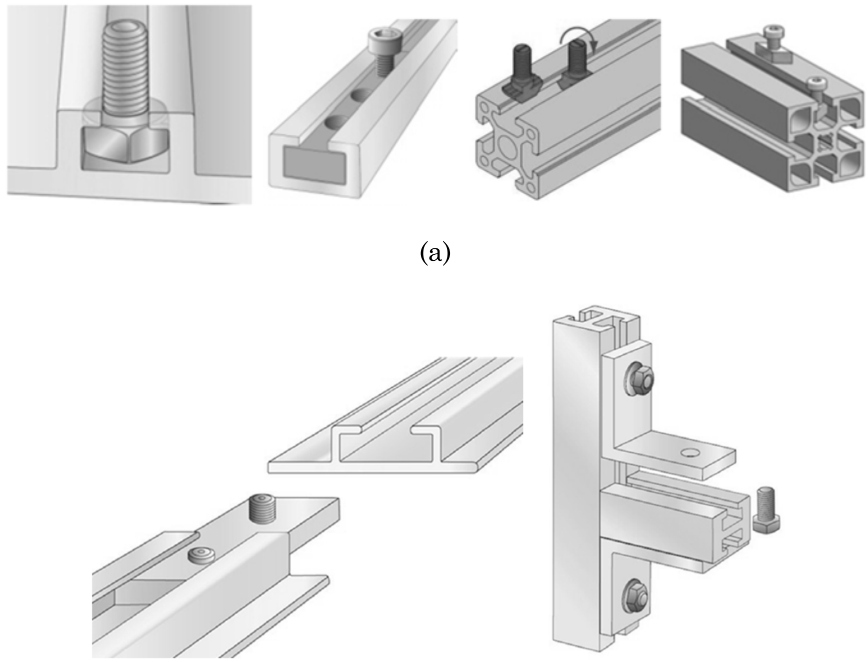
Therefore, the innovative content of these joints consists in entailing the extrusion process to obtain specific profiles with cross-section suitable for the accommodation mechanical fasteners. These joints can be used for specific cases and are completely different from conventional bolted and welded joints generally used for aluminum and/or steel structures. The advantages related to these joints are not in terms of structural strength, which is rather lower than conventional bolted joints, involving different failure modes. The effective advantages are technological, because the reduction of additional elements and machining can significantly simplify the execution.

Although the screw port and *bolt-channel* joints are widely used in structural applications, little literature is available. In particular, an experimental campaign on a specific screw port typology (*screw-groove*) and bolt channel joints was conducted by Hellgren [5], other tests on *screw-groove* joints were performed by Menzemer et al. [11]. In the main international codes, there are little information about the design of this joints with the exception of the aluminum design manual (Aluminum Association [1]), which provide design formula for the pull-out resistance of open and closed configurations of screw port. On the other hand, Eurocode 9 (CEN [2]) specifies that their use is possible only if appropriate experimental tests are carried out (design assisted by tests). Some information about the design and the geometry of the extruded parts are given by manufacturers' manual, such as Sapa [12] and Hydro [6]. However, the available formulations for strength prediction are generally obtained on experimental data and are limited to the investigated cases or configurations for given ranges of validity. The aluminum industry showed a great interest about special joints due to the several advantages related to their use. But, at the same time, due to the lack of information about the design provisions, the manufactures are forced to design these joints by means of expensive experimental tests.

As an attempt to overcome this lack of information, a research on the mechanical behaviour of special joints was undertaken at University of Naples "Federico II" with the financial support of METRA S.p.A (Macillo [8]; Macillo et al. [9]; and Fiorino et al. [3]). In order to define the main issues related to the joint geometry, the influence of load type and the joint structural response, an extended study on *bolt-channel* joints and different typologies of screw port systems has been carried out by means of experimental tests and numerical modelling. The present paper shows in detail the results of the experimental activity. The numerical phase is deeply discussed in Fiorino et al. [4] and Macillo et al. [10].

2. Bolt-Channel and Screw-Port Joints

The *bolt-channel* joint system consists in an extruded section with a track, where the head or nut of bolt connecting the profile to the other joint components is located (Figure 1). This joining technique allows to set the bolts anywhere along the profile length without any machining, with the possibility of ease relocation by moving the bolt head along the track (Sapa [12]). In the case of joints with more bolts disposed at a given distance, a plate with threaded holes can be introduced in the track defining the bolt position. In general, plates with threaded holes can be located into the channel and used as nuts. As an alternative solution, special bolt or nuts can be used. For instance, T-bolts has the advantage to be installed directly in the given position without the need to slide it from the end of the profile, or rhombus nuts that, after turning, result self-locked inside the channel.



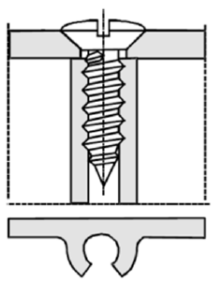
(a)

(b)

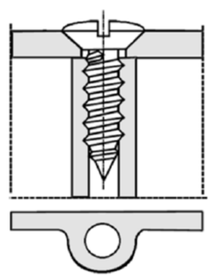
Figure 1. Bolt-channel joint: (a) different fastening systems and (b) possible joint applications (Sapa [12]).

Screw port joints are commonly used to join aluminum profiles for different structural and non-structural applications. This system usually consists in an open or closed slot, obtained by extrusion, in which a screw is installed. The screw port or slot can be threaded by machining when metric screws are used, even if the most common solutions is represented by self-tapping screws. The screw port may have different configurations, as shown in Figure 2.

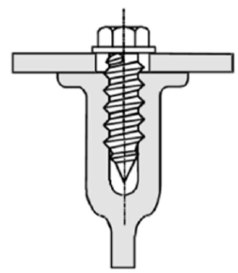
The *screw-groove* (Figure 2(a)) configuration consists in an open slot obtained by extrusion, in which the screw is engaged in the longitudinal direction of profile. The slot opening is usually 60° and it can be located in correspondence of corners or along flat elements of the section. This configuration requires an irrelevant additional amount of material, but the fabrication costs are significantly lower compared to conventional methods of drilling and threading screw holes (Hydro [6]). Closed port configuration, named in this work *screw-tube* (Figure 2(b)), develops longitudinally to the profile. They are present in extruded profiles and, more frequently, in solid aluminum blocks. Closed ports are often used in case where large screw diameters are required (Sapa [12]). *Screw-boss* (Figure 2(c)), or also screw chase, is a system consisting in a channel of the extruded profile in which a screw can be located perpendicular to the profile axis. Possible joint application provided by Sapa [12] are shown in Figure 2(d).



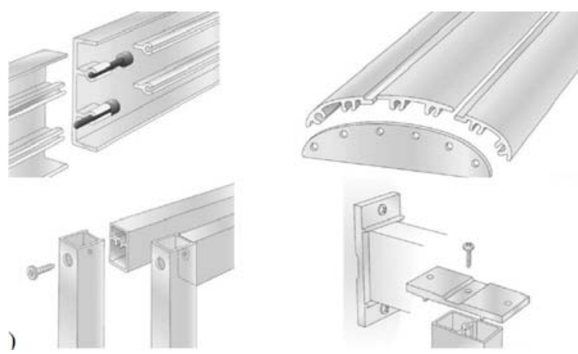
(a) Screw-groove



(b) Screw-tube



(c) Screw-boss



(d)

Figure 2. Screw port configurations (a) screw-groove; (b) screw-tube; (c) screw-boss (modified from TALAT [13]); and (d) possible joint applications (Sapa [12]).

3. Experimental Program

In order to characterize the structural response of *bolt-channel* and screw port systems, an experimental program including 71 tests on joints has been defined.

The tested *bolt-channel* (BC) joints are made by locating a steel plate with a threaded hole located in the aluminum channel. These holed plates are named plate nuts because they behave as a bolt nut. No information, tests results and design rules are, presently, available for this joint configuration. Two extruded AW 6005A-T6 aluminum channels (Figure 3), suitable for M10 and M18 bolt diameters, have been selected as a part of commercial profiles to obtain the BC specimens. The bolts used were 8.8 steel grade, while plate nuts are made of S355 steel. In order to take into account the possible loading conditions that can occur in the different applications of BC joints, three different load directions are considered (Figure 4). The first load direction (SL tests) consists in a force parallel to the track that induces a slipping of bolt and plate nut along the aluminum channel. Three SL series are tested, one for M10 specimens and two for M18 specimens; in order to evaluate the effects of bolt preload, two values of tightening torques are used for M18 specimens. The second load direction (SH tests) is a transversal shear force perpendicular to the channel axis, which brings the plate nut in contact with the channel web. The third load direction (PO tests) consists in a tension force that tends to pull-out the plate nut from the aluminum channel. The whole test program, including 26 tests (14 for SL tests, 6 for SH tests, and 6 for PO tests), is summarized in Table 1, where the different parameters under investigation are given for each specimen series. The series label defines the specimen typology. Namely, the first group of characters (BC) means *bolt-channel*, the second group represents the loading direction (SL: slip, PO: pull-out, and SH: shear), the third group of digits indentifies the bolt diameter (10 or 18mm) and the final character (A or B) distinguishes the equal specimens with different tightening torque.

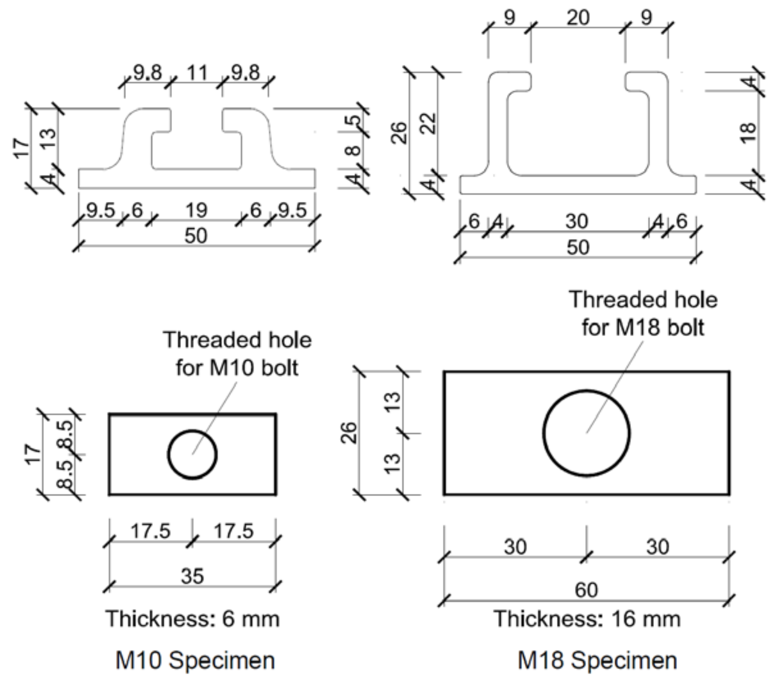


Figure 3. *Bolt-channel* specimens.

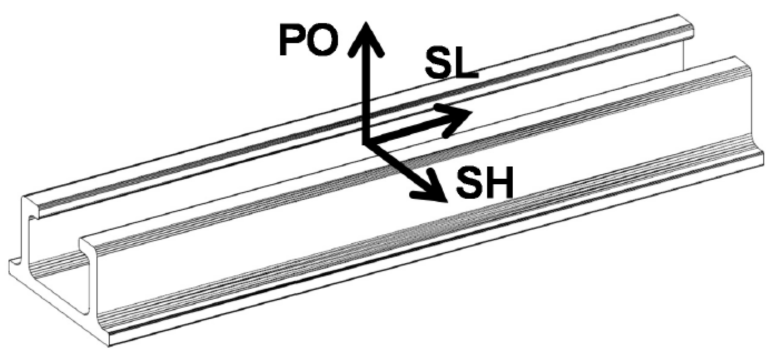


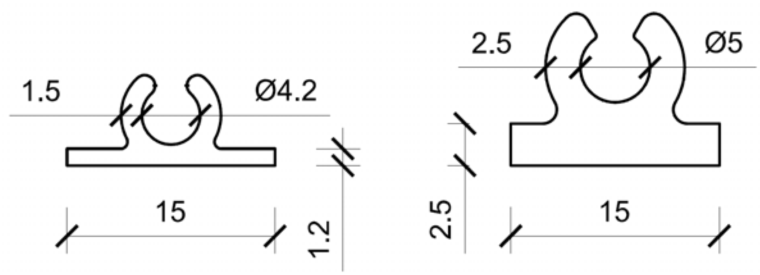
Figure 4. Test load directions.

Table 1. Test program for BC joints

Series Label	Load direction	Bolt diameter [mm]	Tightening torque [Nm]	Aluminium alloy	n. test
BC-SL-10	Slip	M10	40	AW 6005A-T6	6
BC-SL-18A	Slip	M18	93	AW 6005A-T6	4
BC-SL-18B	Slip	M18	60	AW 6005A-T6	4
BC-SH-10	Shear	M10	40	AW 6005A-T6	3
BC-SH-18	Shear	M18	100	AW 6005A-T6	3
BC-PO-10	Pull-out	M10	–	AW 6005A-T6	3
BC-PO-18	Pull-out	M18	–	AW 6005A-T6	3
				Total n. of tests:	26

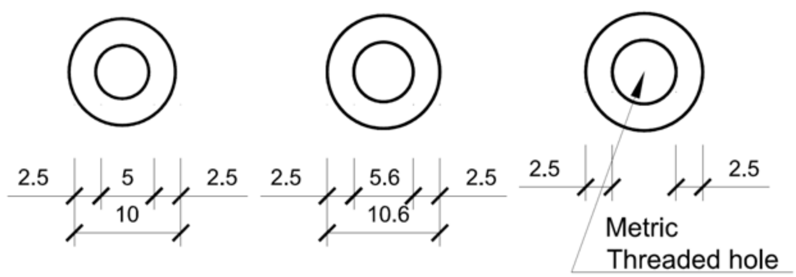
As far as screw port joints are concerned, three different typologies have been investigated. In particular, 13 *screw-groove* (SG), 28 *screw-tube* (ST), and 4 *screw-boss* (SB) specimens have been tested. The investigation parameter for SG and ST specimens are: the aluminum alloy, screw diameter, thread type (self-tapping and metric screws), and nominal embedment length. The latter one is intended as the total screw length inside the aluminum slot including the point. Two different aluminum slots for SG specimens (Figure 5), corresponding to 4.8mm and 5.5mm diameter self-tapping screws, are selected. The specimens are extracted from extruded profiles made of AW 6060-T5 alloy. The ST tubular specimens (Figure 6), corresponding to 5.5mm, 6.3mm self-tapping screws and M6 metric bolts, are obtained by means of the turning process from an extruded bar of AW 6082-T6 alloy. The M6 bolts are made of two steel grades (8.8 and 12.9) and, in this case, the aluminum tube has a pre-threaded hole. The SB specimens (Figure 7) consist of two extruded elements (AW 6060-T5 alloy) coupled by means of two 6.3mm diameter self-tapping screws engaged in a knurled screw channel in order to facilitate the tapping operation. The test program is summarized in Table 2, where the parameters under investigation are reported for each specimen series. The first group of characters of the series label indicates the joint typology (SG: *screw-groove*; ST: *screw-tube*; and SB: *screw-boss*);

the second group represents the fastener diameter (4.8, 5.5 or 6.3mm for self-tapping screw; M6 and M6H for metric bolt of 8.8 and 12.9 grade, respectively); the third group of digits identifies the nominal embedment length (7.5, 10, 15 or 30mm).



(a) (b)

Figure 5. Cross-section of (a) SG-4.8 and (b) SG-5.5 specimens.



(a) (b) (c)

Figure 6. Cross-section of (a) ST-5.5, (b) ST-6.3, and (c) ST-M6 specimens.

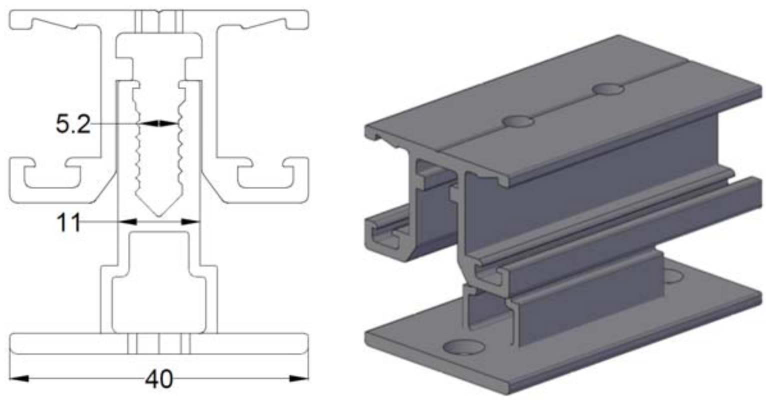


Figure 7. Cross-section and 3D view of SB-6.3 specimen.

Table 2. Test program for screw port joints

Series Label	Screw diameter [mm]	Nominal embedment length [mm]	Alloy	n. test
SG-4.8-15	4.8	15	AW 6060-T5	5
SG-5.5-15	5.5	15	AW 6060-T5	5
SG-5.5-30	5.5	30	AW 6060-T5	3
ST-5.5-7.5	5.5	7.5	AW 6082-T6	5
ST-5.5-10	5.5	10	AW 6082-T6	5
ST-5.5-15	5.5	15	AW 6082-T6	3
ST-6.3-10	6.3	10	AW 6082-T6	2
ST-6.3-15	6.3	15	AW 6082-T6	2
ST-M6-10	M6 (8.8)	10	AW 6082-T6	3
ST-M6-15	M6 (8.8)	15	AW 6082-T6	5
ST-M6H-15	M6 (12.9)	15	AW 6082-T6	3
SB-6.3-15	6.3	15	AW 6060-T5	4
			Total n. of tests:	45

All the tests are performed by using the universal test machine MTS 810 in displacement control with a loading rate of 0.02mm/s and the data are recorded with a frequency of 10Hz. In addition, as a completion of the experimental campaign, the mechanical properties of used materials have been defined by means of 6 tensile tests on aluminum alloys and 3 tensile tests on self-tapping screws. The results of material tests are provided in Macillo [8].

4. Bolt-Channel Tests

4.1. Slip tests

The specimens for SL tests consist of 75mm and 100mm long aluminum channels for M10 and M18 configurations, respectively. Inside the channel, the plate nut is located at a depth of 5mm with respect to the top edge. The M10 specimens are tightened with a torque of 40Nm, which corresponds to 60% of the maximum preloading force (20kN). In the case of M18 specimens, two different torque values, 60Nm and 93Nm, are considered. These values correspond to 25% (26kN) and 15% (17kN) of maximum preloading, respectively. The used torque values are assumed to limit the excessive deformation of the aluminum parts induced by tightening operation in the small thickness elements of the aluminum channel.

The specimen is placed on a steel plate at the bottom and the compression load to the plate nut is applied by means of a steel flat plate clamped in the top wedge grip of the testing machine. The displacement of the plate nut is measured by means of a linear variable differential transducer (LVDT) (Figure 8).

Figure 8. Set-up and instrumentation for SL tests.

The results of slip joint tests are summarized in Table 3, where the values of the average, the standard deviation and the coefficient of variation of slip strength (F_{slip}) together with the average stiffness (*k*) are given. The slip strength of the joint is assumed as the first peak or the plateau of the experimental curve depending on its shape, while the joint stiffness (*k*) is the slope of the first significant linear portion on the experimental curve. The observed failure mechanism is always due to large slipping of bolt inside the aluminum channel, as shown in Figure 9.

Table 3. Experimental results of SL tests on BC joints

Series Label	F_{slip}			k [kN/mm]
	Average [kN]	Standard deviation [kN]	C.o.V.	
BC-SL-10	4.77	0.94	0.20	31.9
BC-SL-18A	7.02	0.97	0.14	37.3
BC-SL-18B	6.88	1.67	0.24	34.5

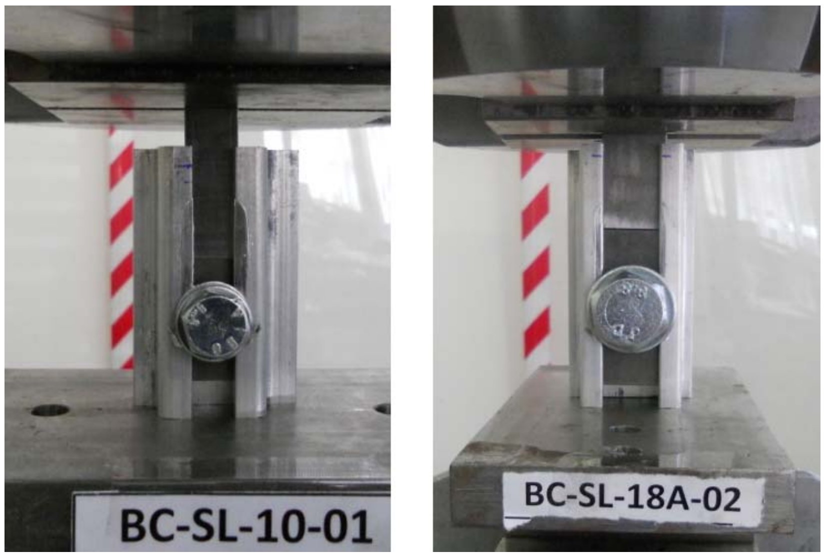


Figure 9. Bolt slipping in SL tests.

Figure 10 shows the experimental results in terms of load vs. displacement (*F*-*d*) curves. By comparing the results of the BC-SL-10 specimens with the BC-SL-18B ones, which are characterized by similar values of preloading force, it can be observed an increase of strength of about 44% with the variation of bolt diameter from 10mm to 18mm. For M18 specimens (BC-SL-18A and B), the variation of 55% of tightening torque implies a very small increase (2%) in terms of average strength.

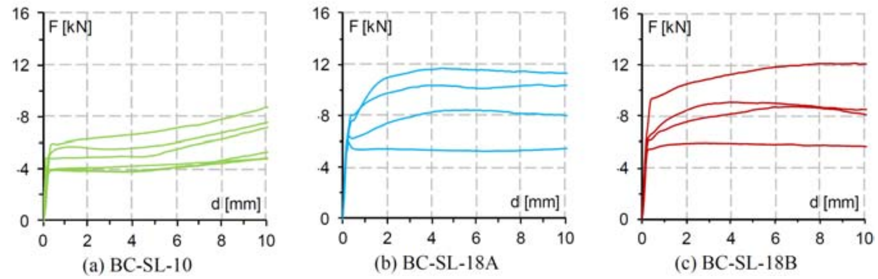


Figure 10. Experimental curves of SL tests.

Then, in the examined cases, the level of torque does not significantly influence the joint response. In addition, it has to be noticed that the results are quite scattered with coefficient of variation (C.o.V.) ranging from 14% to 24%. These findings can be explained by the joint sensitivity to the assembly imperfections. These imperfections consist in a non perfect axial alignment between the channel and the plate nuts because of the tightening, which tends to rotate the plate nut entailing unforeseen contacts inside the channel, so influencing the response. In addition, the tightening operation can cause local permanent deformations of top flanges of the aluminum channel due to the squashing of bolt washer and/or of the plate nuts. These deformations imply a marked material removal during the test sliding, which evidently influences the joint slip strength. In fact, it can be observed that the specimen without evident material removal exhibited a lower slip strength than those having a marked removal of material on both internal and external face of channel top flanges (Figure 11).

Figure 11. Material removal in SL test specimens.

4.2. Shear tests

The test specimens and set-up for SH tests of *bolt-channel* are designed with the aim to reproduce the transversal load transfer and to avoid unwanted or non significant mechanisms. The specimens consist in aluminum channels with length of 250mm and 400mm for M10 and M18 configurations, respectively. The connection under investigation (tested connection) is located in the middle of the aluminum channel and the shear load is applied by using a holed plate clamped the top wedge grip. The aluminum channel ends are connected to a U-shaped steel plate, clamped to the bottom wedge grip of the testing machine. The connections at the ends of the channel are designed to be oversized with respect to the tested ones. All the set-up plates are made of S355 steel grade and their thickness is defined in order to avoid the bearing failure. The bolts are tightened with a torque of 40Nm and 100Nm for M10 and M18 specimens, respectively. The displacements of the tested connection are measured by means of an LVDT placed on bolt head and two additional LVDTs are disposed at the channel ends to measure the displacement of the oversized connections (Figure 12).

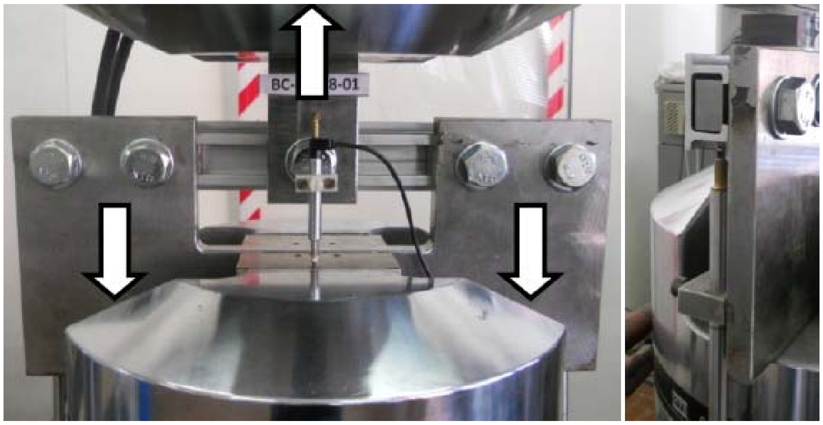


Figure 12. Set-up and instrumentation for SH tests.

Table 4 summarizes the results of SH tests on BC joints. In this table, for each specimen series, the parameters defining the structural behaviour together with the observed failure mechanism are provided. In particular, the values of the average, the standard deviation, and the coefficient of variation of strength ($F_{\max}$) and the average value of stiffness (k) are given. The strength is assumed as peak load of the experimental curve, while the stiffness has been evaluated as the slope of the first significant linear portion on the experimental curve.

Table 4. Experimental results of SH tests on BC joints

Series Label	$F_{\max}$			k [kN/mm]	Failure mode
	Average [kN]	Standard deviation [kN]	C.o.V.		
BC-SH-10	20.8	0.60	0.03	20.4	BF
BC-SH-18	49.3	1.83	0.04	8.32	W
BF: Failure occurred in channel bottom flange					
W: Failure occurred in channel web					

The failure mechanism of the BC-SH-10 series consists in a crack development in the aluminum channel at the bottom flange close to the corner with the web (Figure 13(a)). The specimens present also an evident deformation of top flange and web on the loaded side, while the bolts and the plate nut do not appear significantly deformed. In the case of the BC-SH-18 series, a crack develops from the top flange on the loaded side to all the web depth and along the intersection between the web and the bottom flange (Figure 13(b)). Also in this case, no evident deformations in bolt and plate nut occur.

(a)

(b)

Figure 13. Failure mechanism in (a) BC-SH-10 and (b) BC-SH-18 series.

Figure 14 shows the experimental results in terms of load vs. displacement (*F-d*) curves. The experimental curves exhibit a sudden slope change in the load range from 5kN to 10kN for BC-SH-10 specimens and in the range between 10kN and 15kN for BC-SH-18 ones. This can be ascribed to the sliding due to the clearance between the plate nut and the aluminum channel as well as between the hole of the set-up plate and the bolt. It can be also observed that the two investigated configurations show a great variation in terms of deformation capacity. In terms of strength, an increase of 137% from BC-SH-10 to BC-SH-18 is observed. On the contrary, BC-SH-10 specimens resulted 2.5 times stiffer than BC-SH-18 ones. This result, consisting in a stiffer response of the joint with the smaller bolt, can seem counter-intuitive, but it is justified by the quite non-rational geometry of the BC-10 cross-section, which has stiffer webs with respect to the BC-18 one (Figure 3). In addition, the strength values for both series are very little scattered with coefficient of variation lower than 4%. The low scattered values demonstrate that, for the investigated cases, the shear strength of *bolt-channel* joint is not affected by assembly imperfections, as also confirmed by the symmetrical global response up to the failure.

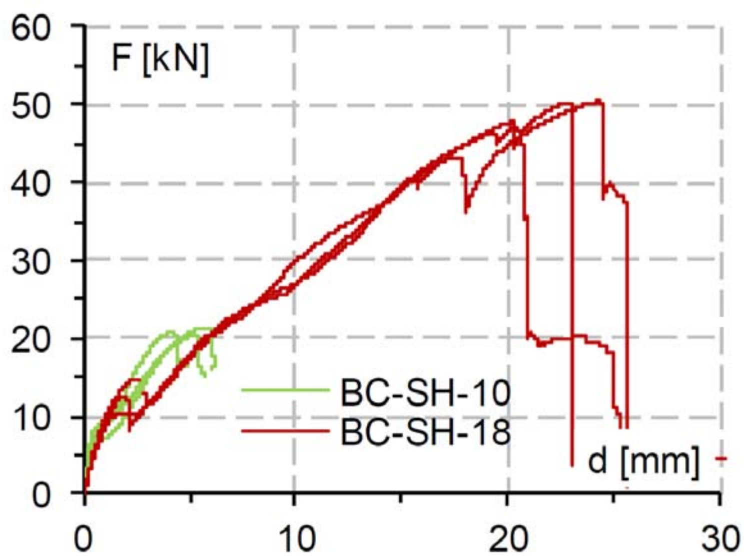


Figure 14. Experimental curves of SL tests.

4.3. Pull-out tests

The specimens for PO tests are 200mm long aluminum channels for both M10 and M18 configuration. The test set-up consists of a T-shaped element, made of S355 steel grade, which is clamped to the bottom wedge grip of the testing machine. The aluminum specimen is fixed to the steel element by means of 4 M10 bolts of 12.9 grade, placed inside the channel. The tested connection is located in the middle of the aluminum channel and it consists in a plate nut tightened with a 180mm long threaded bar. The other end of the bar is installed in a 20mm thick plate pulled by means of a steel holder clamped in top wedge grip of the testing machine. The displacements are measured through a LVDT placed between the holder and the T-shaped element (Figure 15).

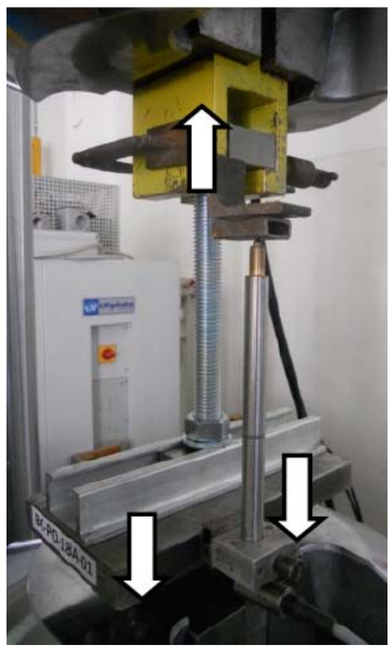


Figure 15. Set-up and instrumentation for PO tests.

In Table 5, the values of the average, the standard deviation, and the coefficient of variation (C.o.V.) of strength $(F_{\max})$ and the average value of stiffness (k), together with the observed failure mechanisms are provided for each specimen series. The strength is assumed as peak load of the experimental curve, while the stiffness has been evaluated as the slope of the first significant linear portion on the experimental curve.

Table 5. Experimental results of PO tests on BC joints

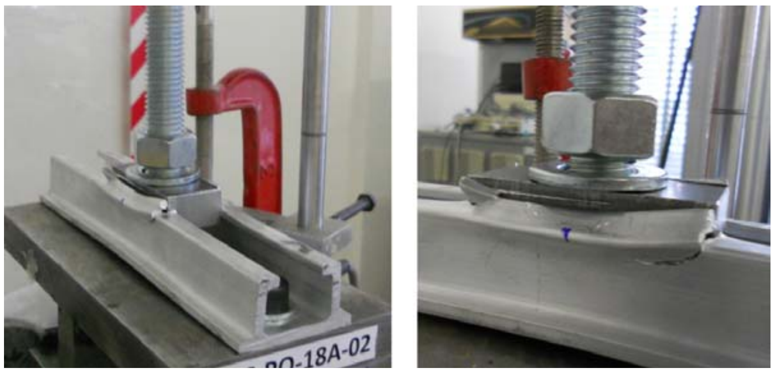
Series Label	F_{max}			k [kN/mm]	Failure mode
	Average [kN]	Standard deviation [kN]	C.o.V.		
BC-PO-10	33.3	0.33	0.01	21.1	PO
BC-PO-18	42.8	2.93	0.07	25.5	TF

PO: Pull-out of threaded bar

TF: Failure occurred in channel top flange

For all the BC-PO-10 specimens, the observed failure corresponds to the pull-out of threaded bar from the plate nut with shearing of both nut and bar threads. In correspondence to the failure, the plate nut results strongly deformed and a crack develops along one of the top flanges of the aluminum channel (Figure 16(a)). The observed failure mechanism of BC-PO-18 series consists in a crack occurred at the one of top flanges, which tends to propagate along the web. In this case, threaded bar and plate nut do not present significant deformations (Figure 16(b)).

(a)



(b)

Figure 16. Failure mechanism in (a) BC-PO-10 and (b) BC-PO-18 series.

It has to be noticed that the response of both series is strongly non symmetrical and it is probably due to assembly imperfection. In fact, the plate nut tends to rotate in the channel because of tightening operation and, due to the clearance, it is not perfectly centered in the channel. This could explain the development of cracks on only one side of the channel. The experimental results in terms of load vs. displacement (*F-d*) curves are shown in Figure 17. It can be observed that the BC-PO-10 series shows a slightly higher deformation capacity with respect to BC-PO-18. The response BC-PO-18 is, in average, 29% and 21% greater than BC-PO-10 in terms of strength and stiffness, respectively. Despite the fact that the joint response is, markedly non symmetrical, for both series, the strength values for both series are little scattered with coefficient of variation lower than 7%. As a consequence, it would seem that the influence of assembly imperfections is evident in the joint deformed configuration, but it does not affect the coefficient of variation of the strength.

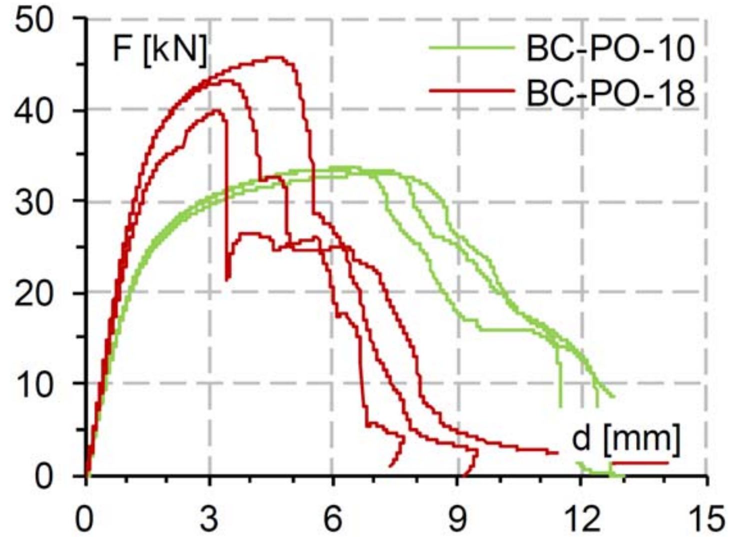
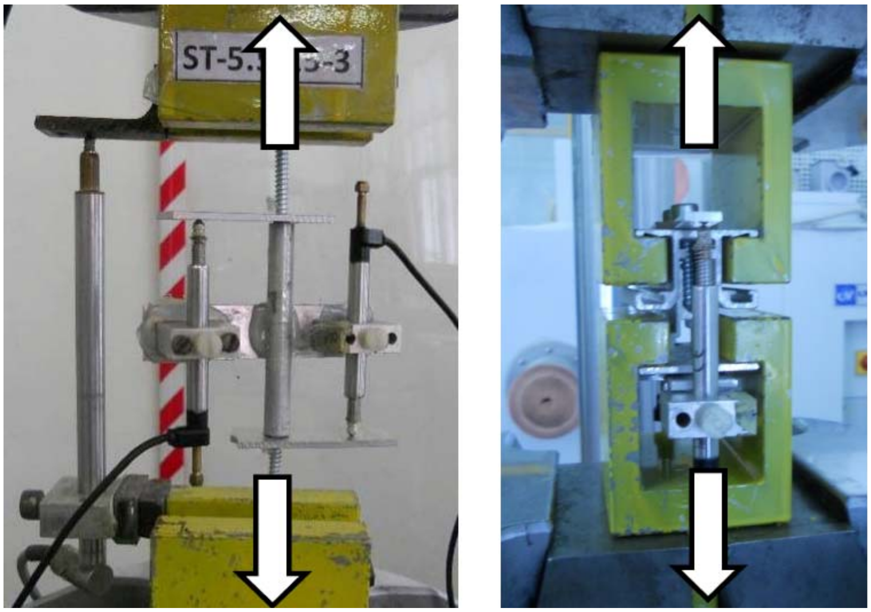


Figure 17. Experimental curves of PO tests.

5. Screw Port Tests

In the case of SG and ST joints, the specimen consists of an aluminum profile, having 80mm length, in which at both ends a screw is engaged for a given length. The tension load has been applied to the specimen by means of two steel holders, clamped in machine wedge grip, in which a steel plate $(38\text{mm} \times 80\text{mm} \times 5\text{mm})$ with a hole in the centre is placed. In the plate hole, the tested screws are installed in such a way to be pulled by the plate through the holder (Figure 18(a)). All the steel parts are made of S355 grade. The SB specimen presents some differences with respect to the other ones. In particular, two screws are placed in parallel position and the load is directly applied to the wings of the aluminum profile through the steel holders (Figure 18(b)). The instrumentation for SG and ST specimens consists of two linear variable differential transducers (LVDTs) for the measure of local displacements at the aluminum slot ends with an additional LVTD for the global response of the specimen. In case of SB specimens only two LVDTs are used.



(a) (b)

Figure 18. Test set-up for (a) SG and ST and (b) SB specimens.

The results of pull-out tests on screwed joints are summarized in Table 6. In this table, the average, the standard deviation, and the coefficient of variation values of strength $(F_{\max})$ and the average values of stiffness (*k*), together with the observed failure mechanism, are provided for each specimen series. In particular, the stiffness values are evaluated as the slope of the first significant linear portion on the experimental curve.

Table 6. Experimental results of pull-out tests on screw port joints

Series Label	F_{max} Average [kN]	F_{max} Standard deviation [kN]	F_{max} C.o.V.	k [kN/mm]	Failure mode
SG-4.8-15	3.62	0.21	0.06	5.06	P
SG-5.5-15	6.10	0.93	0.15	6.66	P
SG-5.5-30	12.60	0.51	0.04	8.48	P
ST-5.5-7.5	7.32	1.26	0.17	8.12	P
ST-5.5-10	12.76	0.71	0.06	9.06	P[1]
ST-5.5-15	14.24	0.27	0.02	9.29	S
ST-6.3-10	9.62	–	–	10.32	P
ST-6.3-15	18.90	–	–	11.46	A
ST-M6-10	14.61	1.41	0.10	8.59	P
ST-M6-15	17.40	0.32	0.02	10.03	S
ST-M6H-15	19.38	0.08	0.003	12.72	A
SB-6.3-152	2.35	0.07	0.03	3.87	P

P: screw pull-out; S: screw failure; A: aluminium failure

1 screw failure occurred for one specimen

2 values per single screw

As far as the SG tests (Figure 19(a)) are concerned, the observed failure mechanism is always the pull-out of screw from its slot due to the shear of the aluminum threads together with the opening of the aluminum slot. In the case of SG-4.8-15 and SG-5.5-30 (Figure 20), the specimens show also a pronounced bending deformation of aluminum slot due to the eccentricity between screw and slot axes. By comparing the results of SG-4.8-15 and SG-5.5-15 specimens, it can be noticed that the influence of the diameter, from 4.8mm to 5.5mm, reveals an increase of strength equal to 69%. In case of SG-5.5, the doubling of the nominal embedment length from 15mm to 30mm implies an increase of about two times of strength (106%). The scatter (C.o.V.) of strength values are in the range from 4% to 15%.

In SB specimens, the screw pull-out failure due to the aluminum thread failure (Figure 21) occurs and, in terms of strength, the values are very little scattered with a coefficient of variation of 3% (Figure 19(b)). By comparing the results of the other open slot specimens with similar nominal embedment length (SG-4.8-15 and SG-5.5-15), it can be noticed that, although a greater screw diameter (6.3mm) is used, the strength per one screw is considerably lower (from 35% to 61%). This strength difference can be explained by the low interaction between the screw and the slot due to a smaller threaded aluminum portion for SB specimen respect to the other systems.

The comparison of the deformation capacity for the SG and SB specimens shows similar values of the ultimate displacement (about 2mm) with the exception of SG-5.5-30 case, in which ultimate displacements of 3mm are observed.

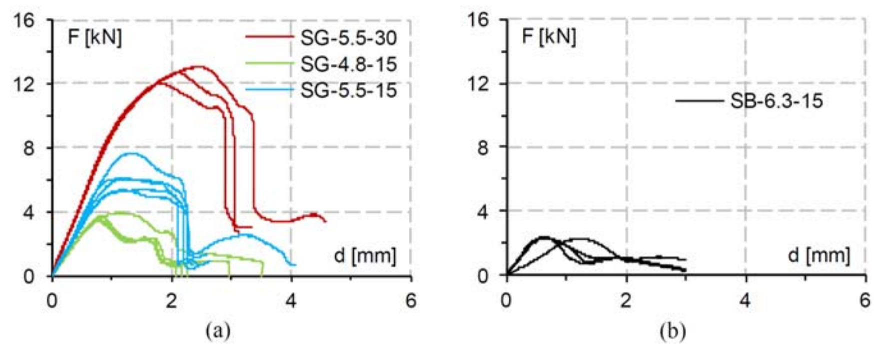


Figure 19. Experimental curves of (a) SG and (b) SB tests.

Figure 20. Pull-out failure of SG joints.

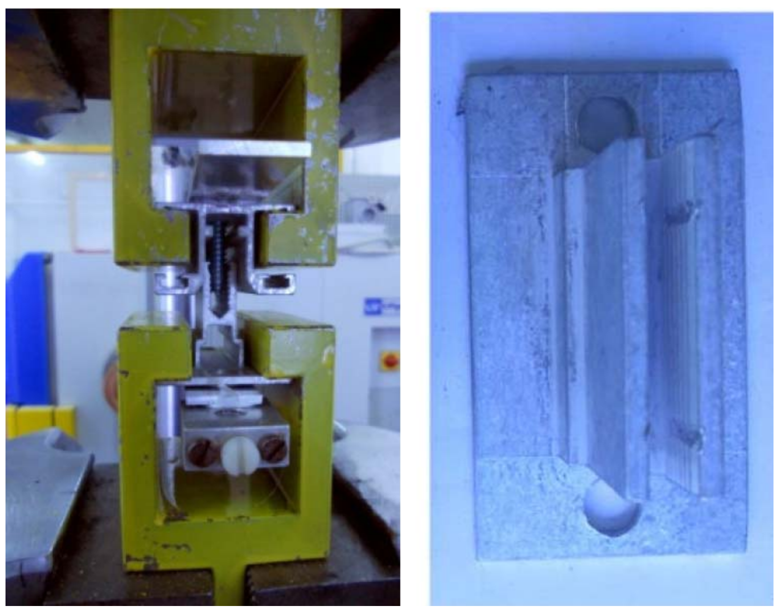


Figure 21. Failure mechanism of SB specimens.

As far as the ST series are concerned, the observed failure mechanisms are three: screw pull-out, tension failure of the screw, and tension failure of the aluminum tube (Figure 22). In particular, the pull-out failure consists in shear failure of the aluminum threads. For all the series having embedment length of 7.5mm and 10mm, the failure is due to the screw pull-out, with exception of only one test of the ST-5.5-10 series where screw failure occurred. Tension failure of screw occurs for the ST-5.5-15 and the ST-M6-15 series, while, in the case of the ST-6.3-15 and the ST-M6H-15 series, the failure of aluminum tube occurred.

(a) (b) (c)

Figure 22. Failure mechanisms in ST specimens: (a) screw pull-out; (b) screw failure; and (c) aluminium failure.

In the case of the ST-5.5 series (Figure 23(a)), the experimental evidence shows a high strength increase (78%) for a little difference of embedment length from 7.5mm to 10mm. This occurs because the parameter influencing the response is the length of the screw portion that fully threads the aluminum slot, namely, effective embedment length, which can be assumed as the difference between the nominal embedment length and the screw point length. The influence of the difference between nominal and effective embedment length is more marked for little nominal embedment lengths. In this case, the point length is 5mm, according to ISO 1478 (ISO [7]) and then the effective embedment length are 2.5mm and 5mm for nominal values of 7.5mm and 10mm, respectively. Therefore, the doubling of the effective embedment length can justify the observed increase of strength. On the other hand, the variation of nominal embedment length from 10mm to 15mm implies an increase of strength of 11% with the change of failure mode. The scatter of strength is in the range from 2% to 17% with higher values for lower embedment length.

By comparing the results of ST-6.3 series (Figure 23(b)), it can be observed a 96% increase of strength from 10mm to 15mm nominal embedment length with a change of failure mode from pull-out to aluminum failure. It can be noticed that the average strength of ST-6.3-10 is 25% lower than the one of smaller diameter (ST-5.5-10). Also this finding depends on the difference of the effective embedment length, because the point length of 6.3mm diameter screws is 6mm and the corresponding effective embedment length for ST-6.3-10 is 4mm, lower than the one of ST-5.5.10 (5mm).

The results of the ST-M6 series (Figure 23(c)) in terms of strength present an increase of 19% from 10mm to 15mm nominal embedment length with a change in failure mode from pull-out to screw failure. By changing the bolt grade from 8.8 to 12.9, the strength increases of 11% and the failure moves to aluminum side. In addition, by comparing the strength results between the ST-M6-10 and the other ST series having the same nominal embedment length, it can be observed that the metric threaded screws shows a strength increase of 14% and 52% respect to ST-5.5-10 and ST-6.3-10. This can be explained by the difference of thread pitch (1mm for M6 bolts and 1.8mm for both 5.5mm and 6.3mm diameter screws) and a lower influence of effective embedment length, which is closer to the nominal one for bolts. The strength values are very low scattered with a maximum coefficient of variation of 10%. Also this case confirms a decreasing trend of scattering with an increase of embedment length. The results in terms of deformation capacity of ST specimens show that, in the case of pull-out failure, the ultimate displacement is about 2mm while, for other cases, displacements up to 9mm are observed.

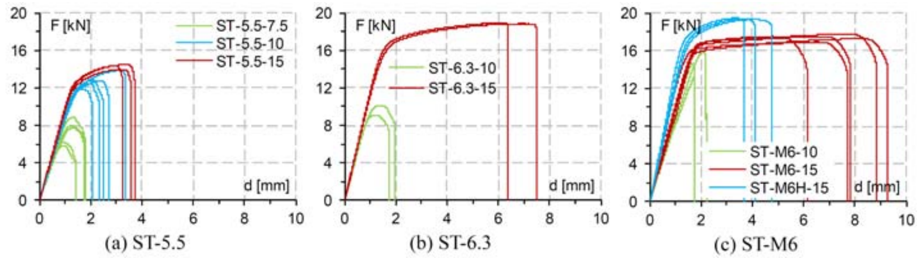


Figure 23. Experimental curves of ST tests.

As a general remark, it can be observed that the most scattered results for ST specimens are always for lower values of nominal embedment length (7.5mm to 10mm). These cases correspond to the failure mode of screw pull-out. Such mechanism is strictly related to the embedment length and then the corresponding strength is very sensitive to little variations of this length. As a consequence, the assembly imperfections, in terms of little difference between actual and nominal embedment length, can strongly influence the structural response.

6. Conclusion

The evaluation of the structural response of *bolt-channel* and screw port joints by means of experimental tests is presented in this paper.

The *bolt-channel* joints are tested under three different loading directions: slip (SL), shear (SH), and pull-out (PO). The SL tests show high scattered results in terms of strength (14-24%) probably due to influence of the assembly imperfections. This issue does not affect the SH tests response, whose deformed configuration is globally symmetric and presents very low scattered values in terms of strength (3-4%). In the case of PO tests, although the strength values are little scattered (1-7%), the exhibited deformed configuration is always strongly non symmetric, probably due to assembly imperfections.

Three different failure mechanisms for screw port joints under pull-out loading are observed: the screw pull-out with the shearing of aluminum treads is the typical failure mode for open port joint (*screw-groove* and *screw-boss*) and also for *screw-tube* joints with little nominal embedment length $(L_n \leq 10\text{mm})$; while in other cases $(L_n > 10\text{mm})$ the screw or the aluminum failure occurs. Pull-out failure presented strength results more scattered, with coefficient of variation ranging from 10% to 17%, than the other cases where the scatter is always lower than 2%. These findings could be ascribed to the higher sensitivity of such mechanism to assembly and imperfection issues.

As a conclusion, the experimental results show the important role of the imperfections and assembly issues on the joint response as well as the shape and the proportions of the aluminum cross-section (slot or track) that may strongly influence both the strength and the failure mechanism.

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