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EXPERIMENTAL CHARACTERIZATION OF THE MULTI-DIRECTIONAL BEHAVIOUR OF ANGLE BRACKETS AND HOLD-DOWNS

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ABSTRACT: The multi-directional mechanical behaviour of angle brackets and hold-downs (i.e. NINO and WKR) is investigated in this study by means of monotonic tests in tensile (F1), in-plane shear (F2/3) and out-of-plane (F4) load configurations. The values of resistance and stiffness for each angle bracket were determined. For WKR hold-downs the load acting on anchor bolt were measured through a load cell. The analyses of results showed that the tested connectors are characterized by significant strength and stiffness for different load configurations, as reported in other experimental campaign for similar connectors where the multi-directional behaviour was investigated.

KEYWORDS: angle bracket, hold down, CLT connections, multi-directional behaviour, monotonic tests.

1 INTRODUCTION

The mechanical behaviour of Cross Laminated Timber (CLT) and Light-Frame Timber (LTF) shearwalls is typically governed by the connections used to either connect the timber elements each other or anchor the wall to either the foundation or the floor below [1,2]. Hold-downs are usually placed on the two vertical edges of the shearwalls in order to limit the rigid body rotation of the wall while angle brackets are uniformly distributed along the entire length of the shearwall to limit sliding. Angle brackets and hold-downs are typically composed with cold-formed steel plate (2-3mm thick) connected to timber elements by means of nails or screws and to the foundation with a threated steel bar. A uni-directional behaviour of hold-down and angle brackets is typically assumed by the designers [3], so that hold-downs are designed to resist a tensile-vertical load (uplift), due to the rocking, while angle-brackets are primarily designed to resist the shear-horizontal actions: interaction between tensile (F1) and in-plane shear (F2/3) loads is neglected.
Recent experimental campaigns show both traditional [4,5,6] and innovative [7] typologies of angle brackets can be characterized by significant strength and stiffness along multiple directions. The results at connection level are confirmed in shearwalls experimental tests where panels were anchored to the foundation through traditional [8] and innovative [9] angle brackets without using any hold-downs. As a result, the bi-directional behaviour of such types of connectors cannot be neglected in design calculations and experimental testing should be conducted by considering multiple direction load configurations. This paper presents the results obtained from an experimental campaign conducted with the aim to characterize the multi-directional behaviour of the new Rothoblass NINO angle bracket (Figure 1a) and WKR hold-down (Figure 1b). The influence on the mechanical behaviour due to different load configurations, fastener patterns, eccentricity between the fasteners in vertical and horizontal flanges, application of washer and geometry of steel plates were analysed. For tested WKR hold-downs, the load acting on the steel bar used to anchor the hold-down to the foundation was measured in order to determine the load amplification factor on the steel bar.

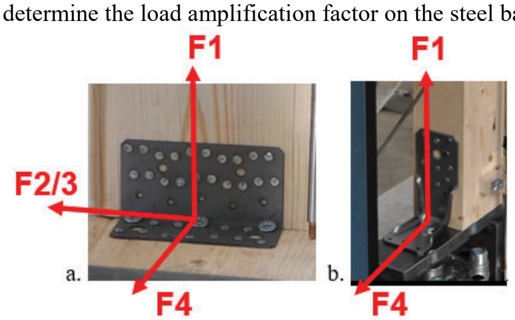

***Figure 1**: a. NINO150100 and b. WKR135 angle bracket*

2. MATERIALS AND METHODS

Rothoblaas NINO angle brackets and WKR hold-downs are obtained from a S235 or S250GD steel plate with different thickness (t) depending on the model. The geometry of each connector (Figure 2) is reported in Table 1. The number and the diameter (d) of holes in vertical flange (Side A) and horizontal flange (Side B) are specified. Holes with d equal to 5mm were used for nails

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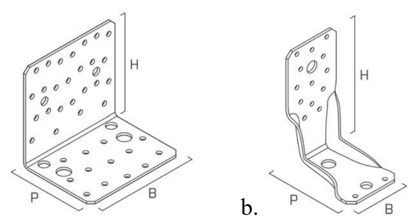
while holes with d equal to 10mm and 14mm were used for screws and bolts, respectively. According to ETA-22/0089 [10], in timber-to-foundation (T-F) connection, NINO15080 and NINO100200 can be installed with specific 6mm thick and 8mm thick washer, respectively.

Table 1: *Geometry of NINO and WKR.*

Con.	b [mm]	h [mm]	p [mm]	t [mm]	Φ5 A	Φ5 B	Φ10 B	Φ14 B
NINO 100 100	104	100	78	2,5	25	13	2	2
NINO 150 80	146	77	55	2,5	25	11	3	2
NINO 100 200	104	197	122	3	49	13	3	4
WKR 095	65	95	85	3	8	-	-	1
WKR 135	65	135	85	3,5	13	-	-	1
WKR 285	65	287	85	3,5	29	-	-	1
WKR 530	65	530	85	3,5	59	-	-	1



a. b.

Figure 2: *Geometry of: a. NINO and b. WKR.*

In timber-to-timber (T-T) connections NINO angle brackets can be installed in two different configurations: with or without screws VGS 9x140mm in the horizontal flange (screwed with an inclination of 15° close to the bend line as for TTV angle bracket [7] in addition to the 4x60mm ring shank nails. The tension loads are transferred from the threaded shank of these screws into the CLT floor panel, avoiding large deformations of horizontal flange. WKR hold-downs have to be anchored in T-T and T-F connection through screw (HBS, TBS or VGS) and M12 threaded rod (in horizontal plate), respectively. Both NINO and WKR connector can be installed with different fasteners patterns in vertical and horizontal flanges, according to [10].

All three different NINO angle brackets were tested along F1, F2/3 and out-of-plane compression (F4) load directions, see Table 2. The WKR hold-downs were conversely tested along F1 and F4 configurations, see Table 3. In some cases of T-F connection an interlayer was interposed to simulate the mortar layer or the concrete curb under the wall panel. The WKR285 was also tested with 10mm gap under the horizontal flange in order to characterized the behaviour of hold-down for particular applications, when there is no contact between the base of connection and the foundation/floor panel.

Sixty-nine monotonic tests were carried out (three tests for each angle bracket or hold-downs for different fasteners patterns and load configuration). Tests were performed according to EN26891:1991 [11]. The load rate was not greater than 0,2 mm/s and the maximum load was reached in 300 ± 120 s in all tests.

In T-T and T-F connections loaded in F1 direction one NINO angle bracket was fastened at each side of CLT wall panel (two angle brackets on each panel) in symmetric configuration and the specimens were tested as shown in Figure 3a and Figure 3b, respectively, while in the specimens loaded in F2/3 direction two NINO angle brackets were fastened at each side of CLT wall panel (four angle brackets on each panel) in symmetric configuration as shown in Figure 3c and Figure 3d, respectively. In T-T connections along F4 direction one NINO100100 angle bracket was fastened at each end of CLT panel, (two angle brackets on each panel), as shown in Figure 3e. For all load directions tested, NINO angle bracket's horizontal flange in T-T connection was nailed (or nailed and screwed) to the CLT floor panel while in T-F connection was bolted to the steel setup.

Table 2: *NINO test configurations*

AB	ID	Load	Type	Fast. Side A	n°	Fast. Side B	n°
NINO 100 100	1	F1	T-T	LBA 4x60mm	14	LBA 4x60mm	13
	2	F1	T-F	LBA 4x60mm	14	M12 bolt	2
	3	F2/3	T-T	LBA 4x60mm	14	LBA 4x60mm	13
	4	F2/3	T-F	LBA 4x60mm	14	M12 bolt	2
	5	F4	T-T	LBA 4x60mm	14	LBA 4x60mm VGS 9x140mm	13 2
NINO 150 80	6	F1	T-T	LBA 4x60mm	20	LBA 4x60mm VGS 9x140mm	11 3
	7	F1	T-F	LBA 4x60mm	10	M12 bolt	2
	8*	F1	T-F	LBA 4x60mm	10	M12 bolt 6 mm thick washer	2 1
	9	F2/3	T-T	LBA 4x60mm	20	LBA 4x60mm VGS 9x140mm	11 3
	10	F2/3	T-F	LBA 4x60mm	10	M12 bolt	2
	11*	F2/3	T-F	LBA 4x60mm	10	M12 bolt 6 mm thick washer	2 1
NINO 100 200	12	F1	T-T	LBA 4x60mm	21	LBA 4x60mm VGS 9x140mm	13 3
	13	F1	T-F	LBA 4x60mm	21	M12 bolt	2
	14*	F1	T-F	LBA 4x60mm	14	M12 bolt 8 mm thick washer	4 1
	15	F2/3	T-T	LBA 4x60mm	21	LBA 4x60mm VGS 9x140mm	13 3
	16	F2/3	T-F	LBA 4x60mm	21	M12 bolt	4
	17*	F2/3	T-F	LBA 4x60mm	14	M12 bolt 8 mm thick washer	4 1

* angle brackets tested with WASHER

Table 3: *WKR test configurations*

HD	ID	Load	Type	Fast. Side A	n°	Fast. Side B	n°
WKR 095	18	F1	T-T	LBA 4x60mm	6	M12 bolt	1
WKR 095	19	F4	T-F	LBA 4x60mm	6	M12 bolt	1
WKR 135	20	F1	T-F	LBA 4x60mm	11	M12 bolt	1
WKR 285	21	F1	T-T	LBA 4x60mm	22	M12 bolt	1
WKR 285	22*	F1	T-F	LBA 4x60mm	22	M12 bolt	1
WKR 530	23**	F1	T-F	M5 bolt	18	M12 bolt	1

* hold-downs tested with gap (10mm)
** vertical flange was also nailed to stud (see Figure 4b)

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3-layer 100 (33-34-33) mm thick CLT panel and 5-layer 140 (30-30-20-30-30) mm thick CLT panel are used in NINO angle brackets experimental tests to represent wall and floor panel, respectively, while a 80mmx160mm C24 solid wood stud is used in WKR hold-downs experimental tests to represent external vertical element of a timber frame.
The vertical flange (Side A) of each connector is fastened to the CLT panel or to the solid wood stud through Rothoblaas LBA 4x60mm ring shank nails (ETA-22/0002 [12]); horizontal flange (Side B) of each connector is fastened to either the CLT panel (T-T configuration) or to the steel base (T-F configuration) by means of Rothoblaas LBA 4x60mm ring shank nails [12] and Rothoblaas VGS 9x140mm screws (ETA-11/0030 [13]) or M12 8.8 steel bolts.

Figure 3: *Setup for: tensile force F1 (a. T-T, b. T-F), shear force F2/3 (c. T-T, d. T-F) and out-of-plane force F4 (e. T-T).*

In WKR hold-down connections loaded in F1 direction (except WKR530) one WKR hold-down was fastened at each side of solid wood vertical stud element in symmetric configuration (two hold-downs on each stud) and tested as shown in Figure 4a (WKR can be noted in the bottom part of the picture). The WKR530 hold-down was bolted directly to the testing machine through M5 bolts and the load was applied directly to the steel plate, as shown in Figure 4b. The vertical flange was nailed to the solid wood stud through twenty-two 4x60mm ring shank nails. In both cases the horizontal flange of hold-down was bolted to the load cell in order to measure the load acting on bolt. Along F4 direction two WKR095 hold-downs were fastened at each end of CLT panel, (four hold-downs on each panel), as shown in Figure 4c.
For each connector the maximum load F_m and corresponding displacement v_m, the load at 15mm F_{15}, the displacements $v_{0,1Fm}$ and $v_{0,4Fm}$ at $0{,}1F_m$ and $0{,}4F_m$ were determined from the load-displacement curves. The tri-linear relationship is determined from the mean force-displacement curve obtained from the three tests in each configuration. The value of yielding load F_y, yielding displacement v_y, ultimate load F_u and ultimate displacement v_u are calculated according to EN12512:2005 [14]. For WKR hold-downs tested in F1 configuration, the load acting on each M12 bolt F_{bolt} that anchored the WKR to the foundation was measured through a load cell. The amplification coefficient k_t, defined as the ratio between the tensile load on the anchoring bolt F_{bolt} and the hold-down F_{WKR}, was calculated according to Equation 1. F_{WKR} for WKR530 is equal to the force F_{app}, measured by the testing machine, while for other WKR hold-downs tested in symmetric configuration F_{WKR} is equal to $F_{app}/2$.

$$k_t=F_{bolt}/F_{WKR} \qquad (1)$$

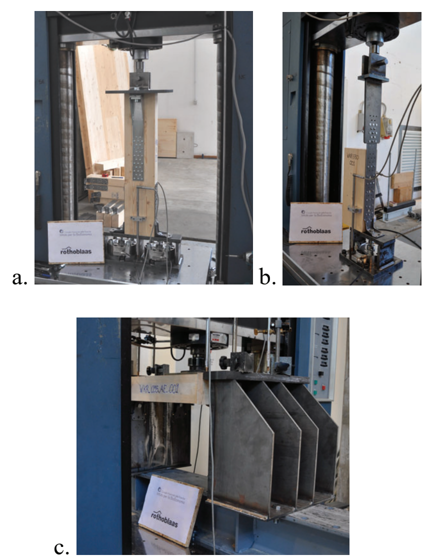

Figure 4: *Setup: a. F1 symmetric, b. F1 WKR530, c. F4.*

3 RESULTS AND DISCUSSION

The results of the experimental campaign on NINO angle brackets and WKR hold-downs are presented in this section. The force-displacement curves, failure modes (Figure 5 and Figure 6 for NINO and WKR connectors, respectively) and tri-linear relationships are reported and discussed.

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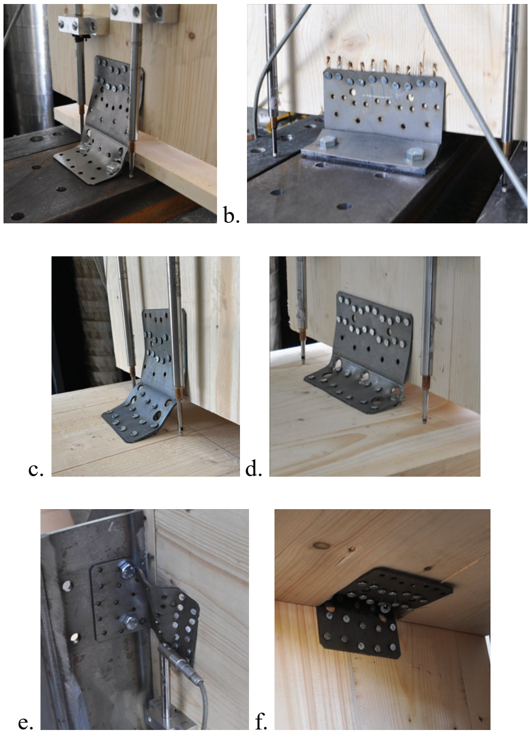
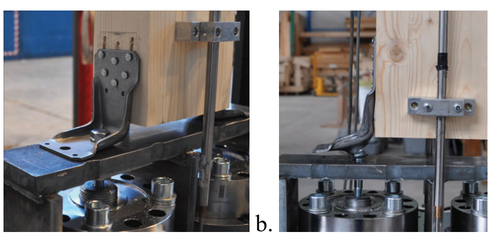


a. b. c. d. e. f.

Figure 5: *NINO angle brackets failure modes: a. pull-through of bolt head (F1), b. nails shear failure (F1), c. nails withdrawal (F1), d. pull-through of screw head (F1), e. buckling (F2/3) and f. compression perpendicular to the grain (F4).*



a. b.

Figure 6: *WKR hold-downs failure modes: a. nails shear failure and b. pull-through of bolt head.*

3.1 NINO ANGLE BRACKETS

Force displacement curves for F1 and F2/3 load directions are reported in Figure 7 (T-F), Figure 8 (T-T) and Figure 9 (T-F), Figure 10 (T-T), respectively.

As shown in Figure 7, in case of T-F connection for F1 load direction, NINO angle brackets equipped with NINO washer showed higher stiffness and strength and a different failure mode compared to the angle brackets without washer: for angle brackets without washer, the failure mode is associated to the pull-through of bolts heads (Figure 5a) in the horizontal flange with large deformation of the steel plate, at the opposite in the angle brackets equipped with washer a ductile failure of nails was observed (Figure 5b).

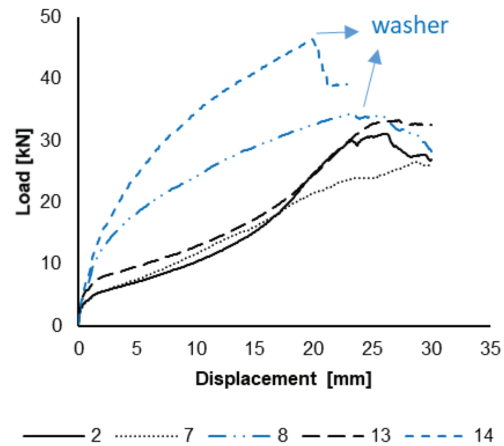


Figure 7: *NINO angle brackets for T-F connection (F1)*

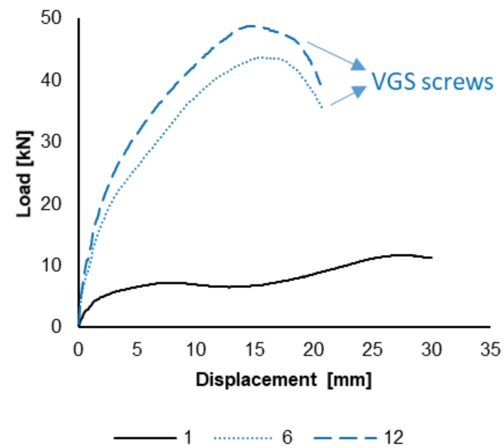


Figure 8: *NINO angle brackets for T-T connection (F1)*

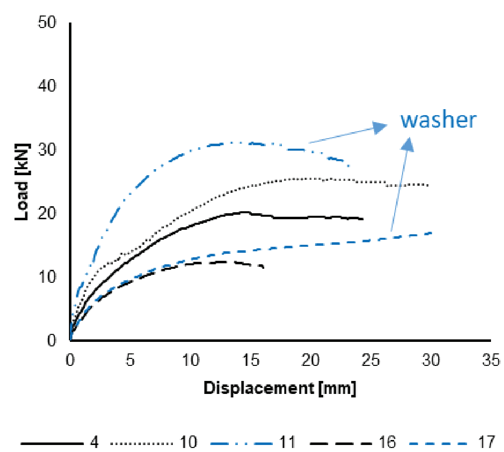


Figure 9: *NINO angle brackets for T-F connection (F2/3)*

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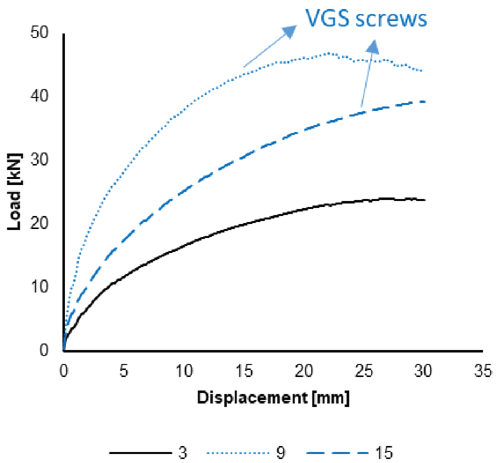

Figure 10: *NINO angle brackets for T-T connection (F2/3)*

As shown in Figure 8, in case of T-T connection for F1 load direction, the NINO angle brackets with VGS screws exhibit a completely different behaviour compared to the NINO without screws when subjected to a F1 load direction. Fully threaded screws installed adjacently to the bend line reduce the eccentricity between the fasteners in the two flanges and significantly increase the strength and stiffness of connections. In NINO angle brackets without VGS screws failure occurs due to the withdrawal of nails in horizontal plate (Figure 5c) while pull-through of screws heads (Figure 5d) or nails shear failure was observed in other cases (depending on the number of nails in vertical flange).

Table 4: *NINO tri-linear curves.*

Con.	ID	k [kN/mm]	vy [mm]	Fy [kN]	vm [mm]	Fm [kN]	vu [mm]	Fu [mm]
	1	3,6	1,1	4,5	27,8	11,6	30,0	11,2
	2	1,5	17,7	28,5	26,1	31,1	29,8	26,8
NINO 100 100	3	2,6	5,6	16,1	27,2	24,0	30,0	23,9
	4	3,0	4,6	15,6	14,6	20,2	24,3	19,1
	5	5,2	5,1	24,2	30,0	44,7	-	-
	6	6,9	4,2	31,8	16,1	43,6	20,8	34,9
	7	1,5	14,6	23,1	28,7	26,5	30,0	26,0
NINO 150 80	8	5,8	2,7	17,7	23,3	34,4	30,0	28,1
	9	8,2	3,1	28,7	22,6	46,9	30,0	43,9
	10	4,3	3,3	16,4	20,8	25,6	30,0	24,6
	11	5,2	4,3	24,9	13,4	31,2	23,3	26,9
	12	8,6	3,5	34,0	14,8	48,8	20,6	39,0
	13	4,3	3,5	17,1	27,2	33,2	30,0	32,6
NINO 100 200	14	5,9	4,9	31,8	19,9	46,4	22,8	39,1
	15	3,7	6,6	26,8	30,0	39,2	-	-
	16	2,7	3,1	9,2	13,1	12,4	16,0	11,5
	17	2,7	3,3	10,0	30,0	16,9	-	-

As for the load direction F1, the angle brackets were tested in F2/3 in different configurations: with and without washer and VSG screws in T-F (Figure 9) and T-T (Figure 10) configurations, respectively. Application of NINO washer or VGS screws allowed to increase the strength and stiffness also in F2/3 load direction, avoiding undesirable failure modes related to large deformations like buckling (Figure 5e) that occurred in some tested NINO angle brackets.
The NINO1001000 angle bracket was also tested in F4 load direction. It was observed remarkable values of strength and stiffness for out-of-plane compression, comparable to the highest values observed in other directions. The connection failed due to the compression perpendicular to the grain (Figure 5f). The tri-linear force-displacement curves parameters were reported in Table 4. The results confirm the marked multi-directional behaviour of NINO angle brackets.

3.2 WKR HOLD-DOWNS

A comparison in terms of force-displacement relationship in F1 load direction is reported in Figure 11 for different WKR hold-downs. The tri-linear force-displacement curve parameters were reported in Table 5.

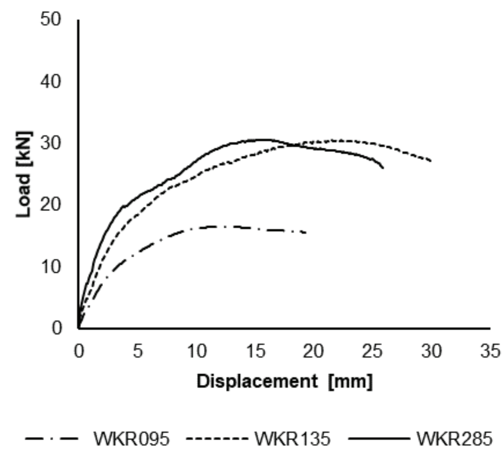

Figure 11: *WKR hold-downs for T-F connection (F1)*

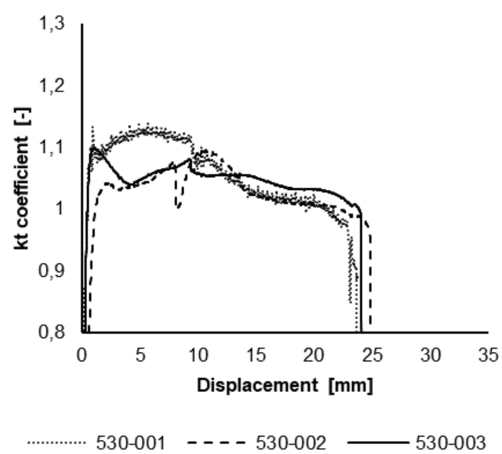

Figure 12*: Coefficient kt for WKR530 hold-down specimens*

In WKR095 hold-downs a shear failure of nails (Figure 6a) was observed while other hold-downs failed due the

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pull-through of bolt head (Figure 6b) in the horizontal flange for a value of the load approximately equal to 30 kN (the geometry of the horizontal flange is the same for all WKR hold-downs): for each WKR size greater than WKR095 the pull-through failure was reached (the shear resistance of nails is greater compared to that of the horizontal steel flange).

For all the WKR specimens in F1 load direction the value of k_t factor was calculated for each hold-down and the maximum values are reported in Table 5. In Figure 12 the values of k_t factors calculated according to Eq.1 for the three tested specimens of WKR530 were showed. The values of k_t coefficient never exceed 1,13, for all specimens. The observed values indicate a slightly difference between the load applied to the hold-down and the load acting on anchor bolt. Moreover, the load amplification on anchor system results lower than that obtained from the formulation proposed in several European Technical Assessment [12] (approximately equal to 1,40). As reported in Table 5, the values of coefficient k_t for WKR285 with 10mm of gap are close to one, that means no amplification of load on anchor system are observed for the hold-downs installed with gap. The WKR095 hold-down was also tested in F4 load direction in order to characterized the out-of-plane behaviour: tests showed good results in terms of strength and stiffness (see Table 5).

Table 5: *WKR tri-linear curves.*

Con.	ID	k [kN/ mm]	vy [mm]	Fy [kN]	vm [mm]	Fm [kN]	vu [mm]	Fu [mm]	kt [-]
WKR 095	18	3,5	3,5	12,7	11,9	16,4	19,2	15,6	1,05
WKR 095	19	3,3	2,6	8,9	30,0	15,1	-	-	-
WKR 135	20	5,0	3,7	19,7	22,3	30,4	30,0	27,1	1,04
WKR 285	21	6,5	2,6	19,4	15,4	30,6	25,8	26,1	1,11
WKR 285	22	6,1	2,0	13,9	14,4	20,6	20,6	16,5	1,00
WKR 530	23	-	-	-	16,0	30,5	-	-	1,13

4 CONCLUSIONS

The mechanical behaviour of NINO angle brackets and WKR hold-downs was investigated by means of monotonic experimental tests. Several setup configurations were specifically developed in order to test the connectors in different load directions. The main novelties of NINO angle brackets are the use of fully threaded screws and washer in horizontal flange in T-T and T-F connections, respectively. The two devices were never used before for small size angle brackets and significantly increase the strength and stiffness in F1 and F2/3 load direction of connectors. F4 tests confirmed a remarkable multi-directional behaviour for all the tested specimens of NINO angle brackets. WKR hold-downs were studied taking into account the possibility to install the connector with a gap between the horizontal flange and the foundation/floor panel. Proper investigations were conducted in order to measure and calculate the coefficient k_t. Tests showed similar results for installation with or without gap for WKR285 hold-down. The amplification of loads on anchor bolts was measured through load cells and can be taken into account by the designers through the coefficient k_t, which results always lower than 1,13. The tests highlight that the value of this coefficient is close to the unit and is smaller than the value obtained from analytical calculation, reducing the design tensile load on anchor system. No amplification was registered on anchor bolts of WKR285 with gap.

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