Brick and Block Masonry – Trends, Innovations and Challenges – Modena, da Porto & Valluzzi (Eds)
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Experimental study on the mechanical performance of steel ties for brick masonry veneers

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ABSTRACT: An experimental study was carried out to analyse the tension and compression behaviour of wall ties anchoring brick veneer walls to masonry infill walls as the backing support. Connection subassemblies were tested under monotonic and cyclic loading, simulating out-of-plane loading of veneer wall systems in order to understand the influence of six different ties with different design, thickness and attachment methods in the strength, stiffness and failure modes of the connection system. Experimental results from this study show more details about the behaviour of this system and importance of determined parameters. Tensile resistance capacity can be more influenced by wall tie design, while tie thickness was considered to be the most important parameter in compression behaviour. Attachment methods studied do not considered a very influential factor. This study can help to understand and justify the contribution of these elements for the mechanical masonry veneer walls under different loading conditions.

1 INTRODUCTION

Brick veneer masonry is frequently used as a façade finishing in residential construction in several countries in different parts of the world, namely North America, Australia, England and other European countries due to its aesthetic appearance, durability and its thermal potential performance. Typically, brick veneer walls are separated from an air cavity to a backing system to which it is attached, like light wood or steel frame, structural masonry or masonry infill walls in conjunction with reinforced concrete frames. The backup system is considered as the primary lateral load-resisting system and the brick veneer is considered to be non-structural. The brick veneer walls are attached to the backing system through distinct types of ties, generally from steel and having different shapes and geometry, much dependent on the baking system.

The distribution of the load between the backing support and the brick veneer depends on the type of loading, the stiffness of each element, and the stiffness of the connecting ties. Under wind loads, any in-plane or out-of-lane load in the veneer will have to be transferred from the backing through the ties. Inertial forces from earthquakes will load both the frame and the veneer. In both cases, the stiffness of the connecting ties should play a key role in the load distribution (Arumala, 2007, Desai and McGinley, 2013). Taking into account that these walls have revealed vulnerability under recent earthquakes with extensive diagonal cracking and particularly detachment from the backing support (Martins et al., 2014), it is important to analyse the performance of the tie connection at the local and global levels in order to understand the role of these in the global behaviour of the brick veneer walls.

In relation to the cases where the backing system is composed of light frames, the available experimental studies have shown that the seismic performance of residential anchored brick veneer walls is generally governed by tie connection deformation/rupture (nail pull-out and/or fatigue fracture of the ties) and their damage limits in tension (Reneckis and LaFave, 2009). To better understand the mechanical performance and contribution of ties to the response of the brick veneer walls, monotonic and cyclic shear tests were carried out by (Zisi and Bennett, 2011) considering a brick-tie wood subassembly specimens and adopting a corrugated sheet metal tie (serpentine and straight ties) for connecting the brick and the wood stud (Figure 1). From the experimental results obtained, it was possible to conclude that tie shape and bend eccentricity were found to be the most important factors for the shear behaviour of the connection. On the other hand, tie location in the bed joint in relation to head joint, fastener type (screw and nail) and number of fastener along

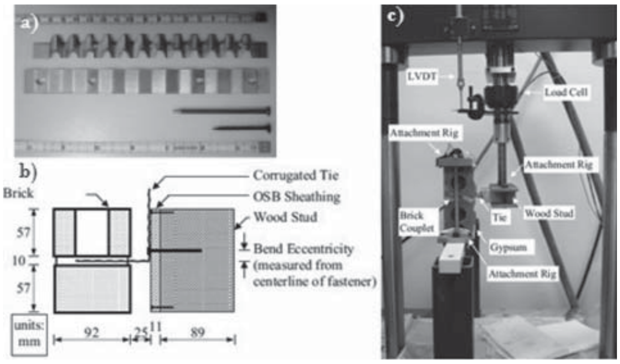


Figure 1. Details of tie connections under shear test: a) tie and fastener types, b) scheme of specimen and c) setup (Zisi and Bennett, 2011).

of the tie in wood were less important parameters in the shear behaviour of the connection (Zisi and Bennett, 2011).

The experimental works carried out by (Choi and LaFave, 2004) and (Reneckis and LaFave, 2009) on shear tests carried out also on brick-tie wood studs assemblages also revealed that twisting tendencies, however, their values for initial and secondary tie stiffness were far more than Zisi, (Zisi and Bennett, 2011)'s stiffness values.

Besides these shear tests, tension and compression tests were also carried out in order to analyse tie thickness (two thicknesses), attaching method of ties (nail and screws), type of loading (including cyclic), bend eccentricity (with sheathing), as well as embedment length of the tie at the bed joint of brick masonry. It was possible to conclude that tie thickness and bend eccentricity affected tension stiffness, whereas embedment length affected tensile resistance.

The predominant tied connection failure mode observed in the monotonic tension tests of nailed subassemblies was nail pull-out from the wood stud, which helped to explain why tie thickness had no effect on average tie connection tensile resistance. During cyclic tension-compression testing of subassemblies with nails, various failure modes were observed (see Figure 2), including nail pull-out, tie fracture, yield around the tie hole (allowing the head of the nail to pass through), and tie buckling (Reneckis and LaFave, 2009).

The same type of tests was done by (Mertens et al., 2014), evaluating three types of wall ties with different diameter; embedment length and type of attaching method (applied in mortar joint or in brick with chemical anchor) in order to improve the design of wall ties, namely quantity of wall ties per square meter. Brick-tie subassemblies were submitted tension and compression monotonic loads. It was conclude that the buckling strength was the determining factor for calculating the number of wall ties per square meter, while for ties with an anchor the pull-out capacity take the major role on the design of the number of ties. Recently, (Ribeiro et al., 2014) studied wall ties as an intervention technique on brick-tie-brick connection subassemblies under monotonic tension loads, aiming at evaluation the connection of a cavity walls. Notice that the application of tied connecting the both leafs of a cavity walls can be viewed as a retrofitting measure, as it will enable to have a more effective thickness and thus a higher resistance under out-of-plane loads induced by seismic action. The ties were fixed though grout injection on bricks holes. The system was studied individually in each leaf and globally considering the subassemblies brick-tie-brick. It was concluded that the grout injection can strongly influences the effectiveness of the solution. Grout workability time and preparation should have adequate fluidity so it can be injected easily in the sock sleeve.

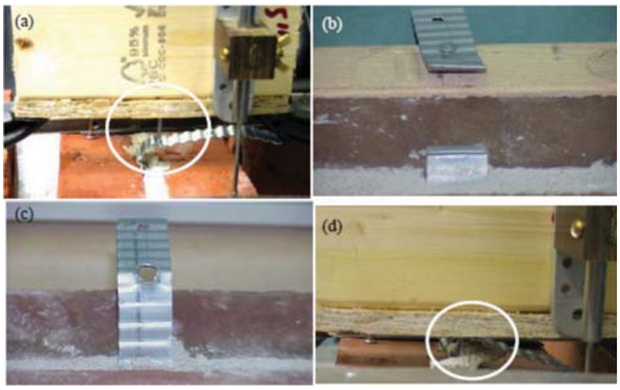


Figure 2. Common tie connection failure modes under cyclic tension-compression loadings: (a) nail pull-out from wood stud, (b) tie fracture, (c) push through of nail or screw head, and (d) buckling of tie (Reneckis and LaFave, 2009).

In the scope of PhD program related to the seismic behaviour of brick masonry veneer walls applied as an external leaf in reinforced concrete buildings, the experimental work presented in this paper has as main goal to analyse the mechanical behaviour of brick-tie-brick assemblages under cyclic tension-compression loading and assess the types of tie on the performance of the connection.

2 MATERIAL AND METHODS

2.1 *Test specimens*

The most common masonry veneer that has been used mainly in reinforced concrete (rc) buildings since two decades ago is an exterior brick veneer leaf attached to a brick masonry infill and sometimes to the rc elements through steel ties.

To characterize the mechanical behaviour of this system to common loading configurations imposed by external action from wind and earthquakes, it was decided to study brick-tie-brick assemblages and evaluate the strength and stiffness behaviour of wall ties with different thicknesses and shapes installed in two different ways, representing common construction practice.

The specimen assemblages are composed of a couplet of brick masonry with typical of running bond representing the brick veneer and the brick masonry infill, see Figure 3. Brick masonry specimen with and without head joints have been considered. The presence of head joints is only in veneer leaf (3 samples) or in masonry bricks infill (3 samples) as explain in Figure 3. This implies that there are two tie positions with respect to the head joint in each leaf in order to make the specimens more representative.

The brick veneer units were approximately 237mm × 115mm × 60mm (length × thickness × height) with vertical perforations. The units and assembled with pre-mixed mortar specially used in brick veneer in construction practice and recommended by bricks's manufacturer. This mortar has a compression strength of 5 MPa (with a coefficient of variation, COV, of 15%) and flexural strength of 3 MPa (with a coefficient of variation of 12%). For masonry infill, brick units with approximately 300mm length, 150mm thickness and 200mm height were selected, taking into account the common typology of the cavity walls used since the eighties. A general purpose mortar (M10) was used to bond the masonry units having a compression strength of 6 MPa (COV of 3.41%) and 2.5 MPa (COV of 6%) of flexural resistance.

Six types of wall ties were considered, as shown in Figure 4, being the general geometric properties indicated in Table 1. Almost all ties are stainless metal ties, with exception of tie type T6, which is composed of basalt fibre. It was considered 6 samples in each typology of wall tie.

All ties were placed at the mortar bed joints of the brick veneer. Apart from the tie T5, all the ties were also embedded at the masonry infill brick masonry (Figure 5 (a)). Tie T5 was attached to the masonry infill lead unit with a chemical anchor (Figure 5 (b)), following the recommendations of the manufacturer and construction practice. The end of wall ties was embedded into the mortar joint of the masonry, being a minimum distance of approximately 60mm in bricks veneer leaf and 70 mm in masonry bricks. In case of tie connected to masonry unit with chemical anchor, the anchorage length was approximately 75mm.

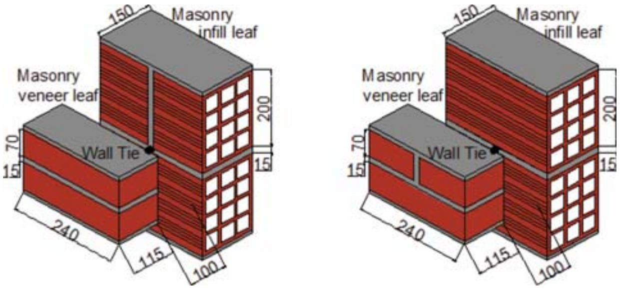


Figure 3. Details of construction of specimen assemblies: (a) head joint in brick veneer leaf and (b) head joint in unit masonry leaf.

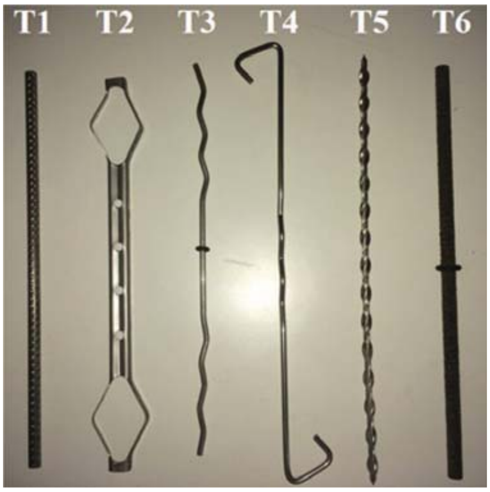


Figure 4. Wall tie typologies used in the experimental campaign.

Table 1. Geometric properties of each wall tie.

	T1	T2	T3	T4	T5	T6
Dimension (mm)	225	225	220	250	245	225
Thickness (mm)	6	5.5/12	3	3	8	7.5

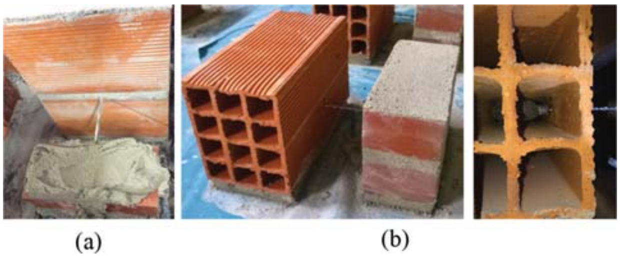
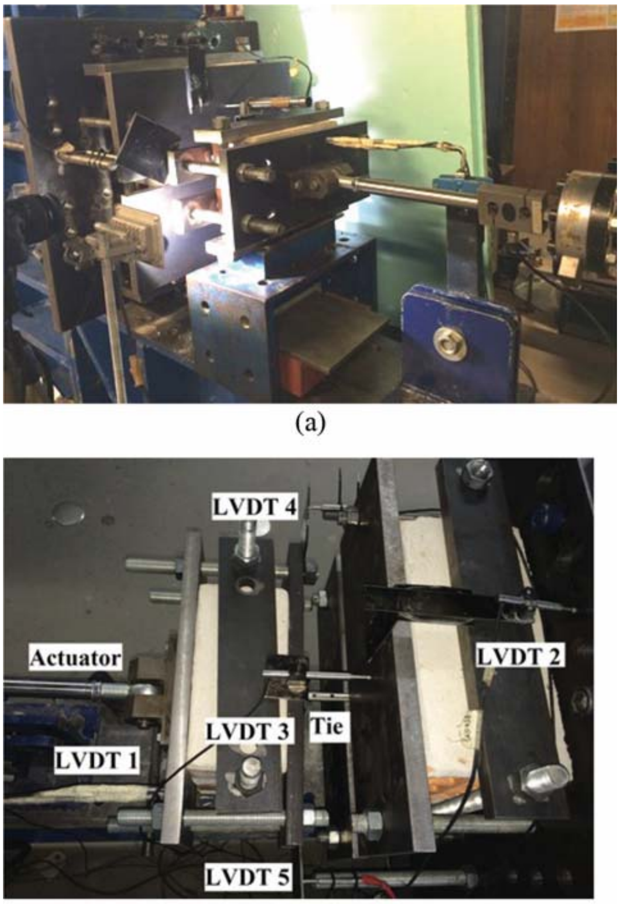


Figure 5. Construction details of the specimens (a) wall ties on brick veneer leaf; (b) T5 wall tie attached to brick masonry leaf.

2.2 *Test setup and test procedure*

The tests were carried out on a stiff steel frame associated with a control system and a data acquisition system linked to a computer that allows the recording of the important information from the tests, namely loads and displacements. The tension and compression load was applied through a hydraulic actuator and measured through a load cell with a maximum capacity of 10 kN, and the linear sliding of the ties was measured by means of 5 LVDT (Linear Variable Differential Transducer) attached to actuator, bricks veneer and masonry bricks, as shown in Figure 6 and Figure 7. The LVDT 1 measured the actuator displacement; the LVDT 2 measured the relative displacement between the stiff steel frame and masonry infill leaf; the LVDT 3 measured the relative displacement between the masonry infill leaf and masonry veneer leaf; the LVDT 4 measured the relative displacement between the stiff steel frame and masonry veneer leaf in superior row and LVDT 5 measured the same but regarding to inferior row.

The two leafs were confined through the use of steel plates previously levelled and connected together, in order to prevent any inadequate deformation of the specimen and to promote the relative displacement between the tie and the leafs in all tie typologies (Figure 6 and Figure 7). In addition, samples were also confined in the transverse direction to the pull-out of the tie, to replicate the real conditions. This boundary conditions has a value between 2% to 3% of the resistant capacity to compression in the same direction at each brick type. A sliding steel roller was installed between the brick veneer leaf and the support to ensure its sliding free of friction.



(a)

(b)

Figure 6. Test setup details: (a) general view and (b) distribution of LVDT.

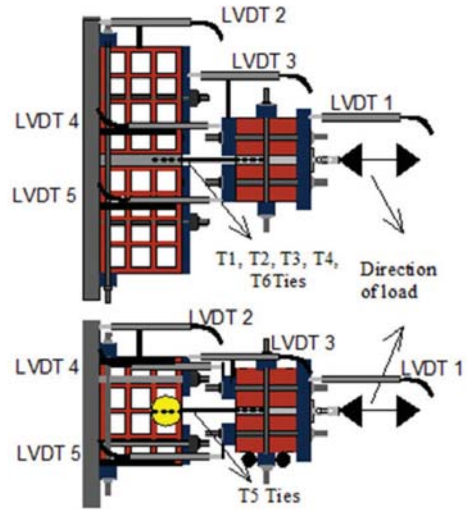


Figure 7. Representative scheme of test setup.

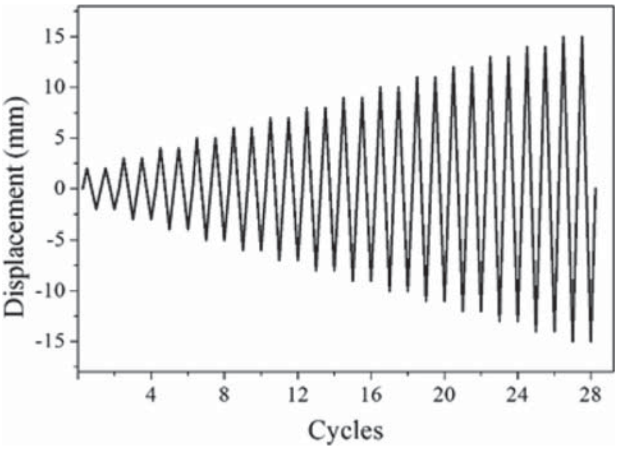


Figure 8. Imposed time-displacement history for cyclic tension-compression tests.

The experimental test was carried out under displacement control at a rate of 0.010 mm/s, which corresponds to a monotonic test duration of approximately 30–45 min.

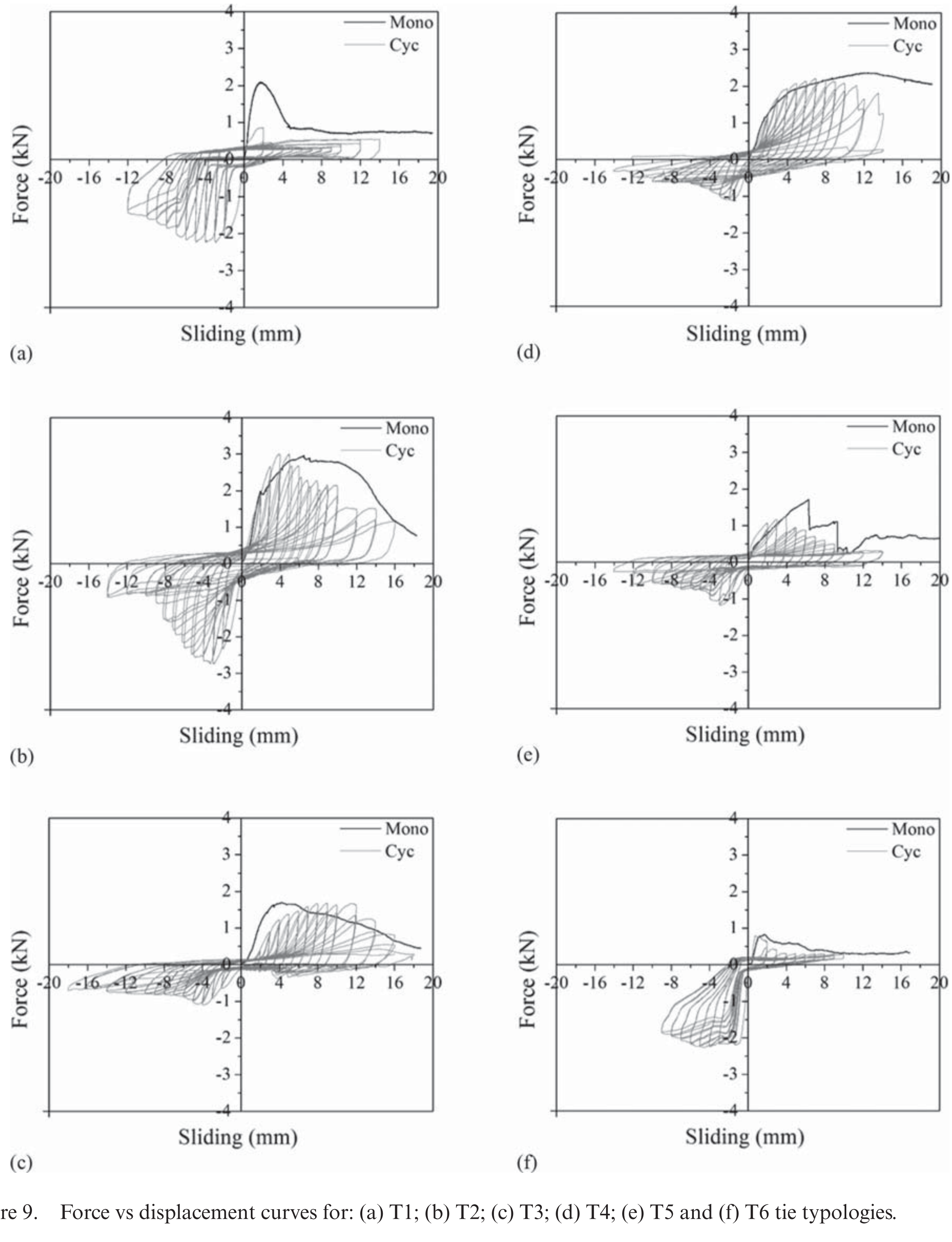
In the cyclic tests, it was considered the displacement law presented in Figure 8 and each cycle was completed in about 200sec, making to total duration of the tests about 60min (and about 28 cycles). The LVDT used to control the tests was the one attached to the actuator. The repetition of the amplitude cycles and the small displacement cycles were included to explore strength and stiffness degradation. All tests were performed at least 28 days after specimen construction.

3 RESULTS AND DISCUSSION

3.1 *Behaviour under cyclic loading*

The behaviour under tension-compression cyclic loading was evaluated in a first stage by means of the force-displacement diagrams presented in Figure 9.

From the force-displacement diagrams some key parameters were derived in order to better analyse and compare the different connection solutions, namely the tensile resistance (Fmax), corresponding displacement (δmax) and initial stiffness (E), whose values are summarized in Table 2. The tensile resistance of each connection is defined as the maximum tension load achieved during testing. The tensile and compression stiffness is defined as the secant stiffness of the load vs. displacement curve up to a tension load correspondent to an opening



(a) (b) (c) (d) (e) (f)

Figure 9. Force vs displacement curves for: (a) T1; (b) T2; (c) T3; (d) T4; (e) T5 and (f) T6 tie typologies.

Table 2. Brick-tie-brick connection subassembly types and average test results.

		Fmax (kN)	C.O.V (%)	δmax (mm)	C.O.V (%)	E (kN/mm)	C.O.V (%)
Compression loading	**T1**	2.61	2.38	4.49	43.45	1.08	23.53
	T2	3.19	25.09	2.73	46.51	1.18	20.91
	T3	1.24	17.76	3.03	47.01	0.33	30.00
	T4	1.21	14.89	2.45	58.44	0.57	8.92
	T5	1.32	16.85	2.71	53.20	0.51	20.91
	T6	2.49	23.67	5.38	36.44	1.07	29.00
Cyclic tension loading	**T1**	0.98	13.16	1.78	13.94	0.47	10.13
	T2	3.12	24.00	4.68	29.61	0.89	18.32
	T3	1.68	25.00	5.11	73.55	0.20	25.00
	T4	2.35	4.22	9.48	35.35	0.58	17.27
	T5	1.20	27.13	3.37	38.43	0.47	25.37
	T6	1.00	31.12	0.81	25.62	0.41	60.46
Monotonic tension loading	**T1**	2.29	4.23	1.71	21.98	0.96	19.30
	T2	3.13	6.72	8.04	4.40	1.09	33.29
	T3	1.71	27.29	4.56	2.64	0.55	24.20
	T4	2.40	5.55	13.32	3.24	0.58	26.90
	T5	1.82	4.54	7.54	29.82	0.39	19.11
	T6	0.82	6.19	1.66	14.48	0.33	16.28

displacement of 2 mm, final first cycle. These values are plotted in Figure 10, in order to help the comparison among the distinct connections typologies.

Besides the average cyclic and monotonic load vs. sliding curves of various types of connections (Figure 9), envelope average load-displacement curves have been prepared and plotted together in Figure 11. This was done to provide an easy comparison between the different types of tie connections behaviour in an average sense.

It is observed that nonlinear hysteretic behaviour is present since small displacements, in almost all specimens, with exception the T2 tie connections that presented an initial linear behaviour. The hysteresis loops are never symmetrical, resulting from the different behaviour of the tie connection under tension and compression.

Pinching effects is less pronounced in subassemblies that presented higher tensile and compression resistances, but becomes pronounced with the increase in displacements in all samples. The reduction in energy dissipation is caused by irreversible damage in the mortar joints in case of tensile damage and buckling of the tie in compression.

From the analysis of envelope curves shown in Figure 11, it is possible to identify two groups of tied connections with similar behaviour in terms of strength both in tension and compression loading. The connections with tie T2 presented simultaneously the maximum compression and tensile capacity. This wall tie is different from the other ties due to its geometry properties and it is considered that it works much better than others due to the interlocking developed at on bed joint in tensile loading and due to its thickness and shape in compression loading. Besides that, connections with other wall ties that had similar design configurations at the tie end, presented also a good behaviour under

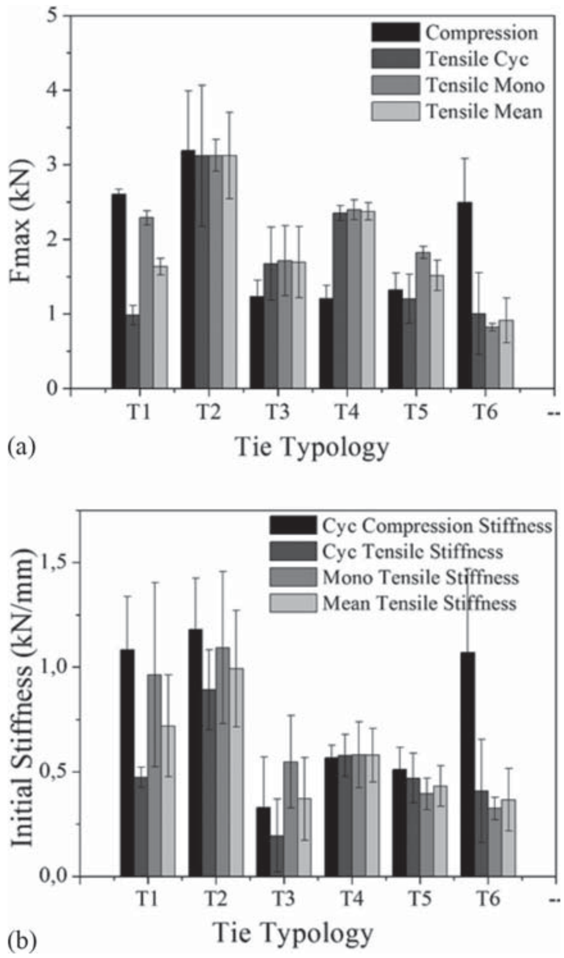


Figure 10. Maximum values of tension and compression resistances and tensile and compression stiffness.

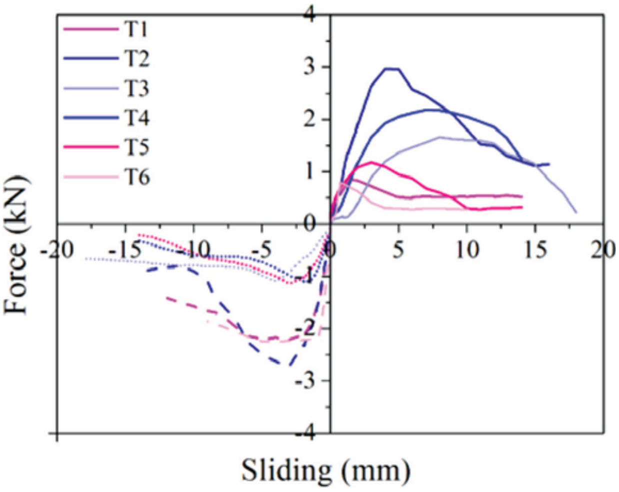


Figure 11. Mean envelopes force vs. displacement curves from cyclic tests.

tension, like T3 and T4 tie typologies. This indicates that the use a thinner tie does not necessarily compromise the tensile resistance of a typical connection, as under tension the bond adherence should role the behaviour of the connection. On the other hand, in compression stages, connections with these wall ties typologies (T3 and T4) do not exhibited a good result. Contrarily, connections with T1, and T6 ties typologies presented a less resistance in tensile loading and a good behaviour in compression loading. Indeed, the latter wall ties have a significant thickness comparing to the ties T3 and T4, which is favourable in compression loading. The connections with wall tie type T5, which have different attachment method with chemical anchor, presented a reasonable behaviour comparing to the others. This parameter did not present significant advantages on behaviour of tie.

Regarding to the post-peak behaviour of connections, it is possible to conclude that there is a strength reduction as cycling progresses and sliding increases. The loss of ties contact with mortar causes slippage, resulting in the loading reduction. When the contact is restored, the resistance is recovered. The initial stiffness is higher when the maximum load is higher, meaning that initial stiffness is directly related with maximum strength, as expected.

Tie geometry and bond adherence are the main factors influencing the tensile capacity and stiffness, whereas the thickness of the ties was found to have an important role on the behaviour in compression.

During cyclic testing, various failure modes were observed (see Figure 12), including tie pull-out, tie buckling, tie fracture at middle length and tie fracture at interface of mortar joint.

All of the connection assemblies tested under tension failed by pull-out from mortar bed joints of bricks veneer leaf (Figure 12(a)). This can be explained because the mortar used in the construction of the brick veneer leaf is lower resistance than the mortar used in the construction of the brick masonry infill. Even in case of connections with chemical anchor on brick infill masonry (T5 typology) the tie also pulled-out from mortar as shown in Figure 12(b).

Under compression load all samples exhibited buckling of the tie (Figure 12(c) and (d)). In some cases tie fracture at interface of mortar joint or at mid length occurred, which should be associated to fatigue from the in cyclic loading as shown in Figure 12(e) and (f).

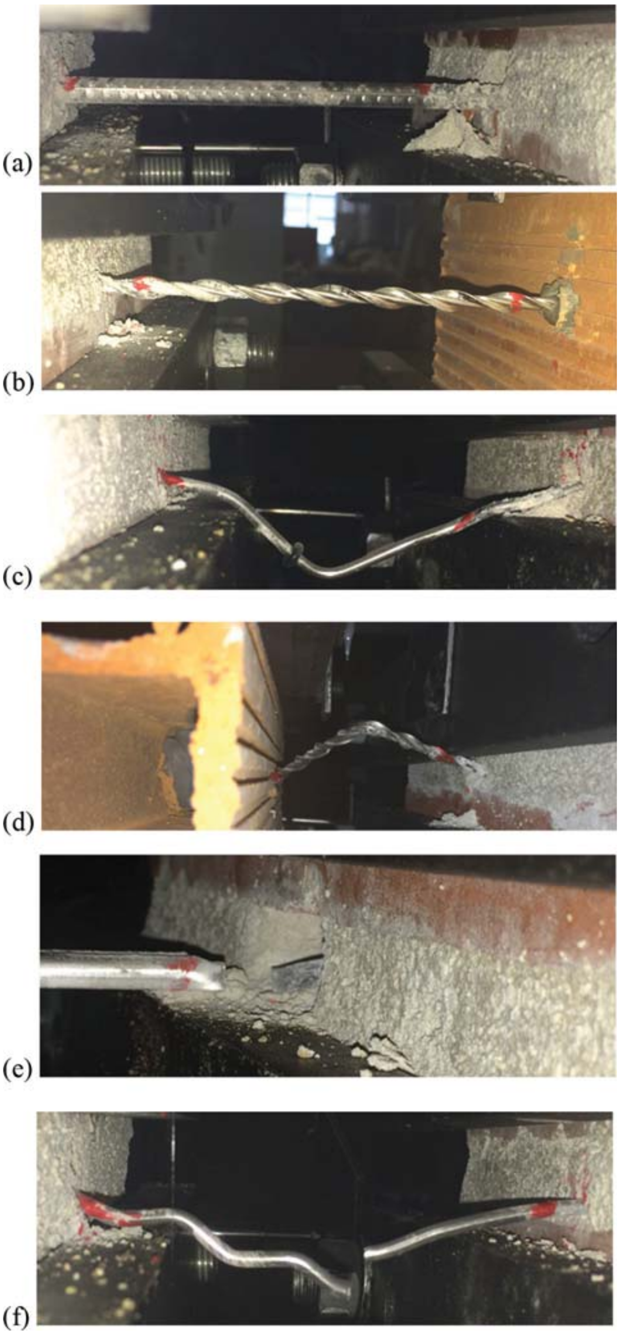


Figure 12. Common tie connection failure modes: (a) and (b) pull-out tie; (c) and (d) tie bucking; (e) tie fracture in interface of mortar and (f) tie fracture in middle of tie.

3.2 *Behaviour under monotonic loading*

The monotonic tests were carried out only under tensile loading and the corresponding force vs diagrams can be seen in Figure 13 (a). The key parameters like maximum strength and corresponding deformation and initial stiffness are summarized in Table 2, together to cyclic tests. Similarly to what was recorded in cyclic tests, the connections with tie typology T2 exhibited the higher tensile resistance. The connections with tie T3 and T4 also presented resistances of the same order and a very ductile behaviour.

In subassemblies with tie T5, the tensile load typically increased before pull-out tie from

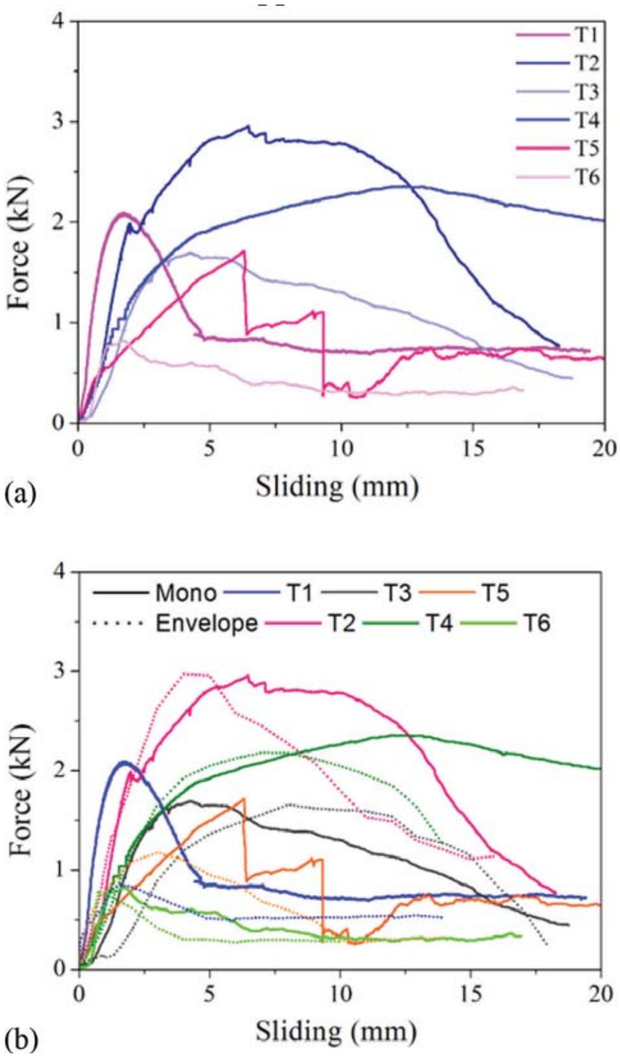


Figure 13. Force vs. displacement (a) monotonic tests and (b) monotonic and envelopes curves from cyclic tests.

mortar from the bed joint and then decreased at very large displacements. Due to helicoidally shape of wall tie, when wall tie began to be interlocked again on mortar joint, the tensile resistance increased. Indeed, the mortar decomposition in cyclic tests was slower and so that this not happen.

On the other hand, the samples with tie T1 presented a reasonable pull-out initial resistance, but taking into account weak bond adherence, the post peak behaviour was very brittle. This behaviour also happened with connections with ties T6 even for low tensile resistance, exhibiting a very weak adherence, possibly due to incompatibility between fibre tie and the bed joints mortar.

The common failure mode of the tie connections under monotonic tension was pull-out of the tie from the mortar bed joint of brick masonry veneer.

3.3 *Monotonic vs cyclic loading*

In general, the maximum force obtained in the connection assemblage under monotonic tension is almost always higher than the maximum force recorded in the cyclic tests.

If in case of connection with tie T2, the difference is negligible and low in the connection with ties T3 and T4, in the case on connection with tie T1, T5 and T6, the difference is considerable. For connections with tie T1 and T5 a reduction of the maximum force recorded in the cyclic tests of about 100% and 50% respectively was achieved.

With respect to the secant stiffness under tension, there is a clear trend when the monotonic and cyclic tests are compared. The secant stiffness of the connections with ties T4, T5 or T6 was very similar in monotonic and cyclic tests, whereas in connections with ties T1, T2 and T3, the secant stiffness was increased by 100%, 22% and 180% in the monotonic tests regarding to the cyclic tests, respectively.

The great difference between monotonic and cyclic envelops regards the post-peak regime, where a more pronounced reduction of the tensile force for increasing displacements was recorded in case of the cyclic tests, see Figure 13 (b). In general, the monotonic envelope curve obtained in the cyclic tests is almost always under the monotonic curve. This behaviour was expected given the damage accumulation during the cycling loading. This means that the load-displacement curve from monotonic tests can serve as a good upper bound approximation to the cycling loading envelope, but some care should be taken to the post-peak regime.

Regarding to the failures modes, the cyclic tests caused more types of ruptures, in some cases tie fracture, due to tie fatigue during cyclic tests.

4 CONCLUSIONS

This paper presents and discusses the experimental results obtained in monotonic and cyclic tension compression tests on connections composed of a coupling of brick masonry specimens through a tie, aiming at representing the local connection of a brick external leaf to a masonry infill wall. This is part of an enlarged experimental campaign of 220 connection involving tension-compression and shear tests. In terms of maximum tension and compression load, there are some differences between connections with different types of ties. The main determining factor in maximum tensile resistance is tie shape and geometry. Indeed, the end of ties with a suitable geometry improves bond adherence and interlocking allowing higher tensile resistance and more ductile behaviour. On the other hand, tie thickness did not appear to influence the tensile resistance but it much significant in the performance of the connection under compression, due to the increased trend for lateral buckling. Regarding to attachment method, the chemical anchor did not indicate improvements on studied solutions.

The cyclic loading is considered to be unfavourable factor both the level of the tensile resistance and failure modes. The failure modes on cyclic testing were basically tie pull-out, tie buckling, tie fracture both at the mid length and at the end of the free length of the tie. All of the connections failed by pull-out from the bed joint of brick veneer leaf under tension. In compression loading stages, all samples exhibited buckling of the tie, presenting in some cases tie fracture at free end or at the mid of the free length due to fatigue induced by the cyclic tests.

ACKNOWLEDGEMENTS

The first author would like to acknowledge the Portuguese Science and Technology Foundation (FCT) for its financial support through grant SFRH/BD/96484/2013.

This work was also supported by FCT (Portuguese Foundation for Science and Technology), within ISISE, project UID/ECI/04029/2013.

This work had an important collaboration with *Ancon Building Products*, an English company, and *Cortartec*, a Portuguese representative company.

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