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PREFABRICATED FOUNDATION SYSTEMS FOR TIMBER BUILDINGS

Davide Canetti[1], Francesca Paoloni[2], Riccardo Fanti[3], Alessandro Setti[4], Andrea Polastri[5], Fabrizio Tamburini[6]

ABSTRACT: Wall-to-foundation constructive detail represent a critical issue for timber constructions due to the risk of decay of wooden components, for this reason the designer has to propose solutions aimed to enhance the durability; furthermore, has to consider several aspects such as mechanical connection, thermal insulation, electrical and plumbing systems. This paper presents an innovative concrete prefabricated beam-foundation element, aimed to solve the issues related to durability avoiding unexpected capillary rise of water creating a physical barrier between the ground and the wooden elements. Experimental tests were conducted to characterized the mechanical properties of the analyzed system: results of the experimental campaign are presented and discussed.

KEYWORDS: timber structures, experimental test, CLT-foundation connection, prefabricated beam foundations

1 INTRODUCTION

In the last decades one of the main issue of timber construction is represented by the timber wall-to-foundation details. The design of this construction detail has to deal with mechanical connection, thermal insulation, electrical and plumbing systems and finally durability. The foundation systems have the fundamental task of transfer loads from the structure to the ground: proper connections to anchor the upper structure to the foundations have to be designed. The shape and type of foundations determined the distributions of loads and deformations, conditioning the bearing capacity of the ground and the behaviour of upper structure. For timber buildings, traditional foundation system consists in a slab at the base of entire structure or foundation beams located below the structural wall, in both cases obtained with reinforced concrete casted in situ. These foundation systems, in case of low-mid rising timber buildings, often results be overdesigned and the high stiffness of traditional reinforced concrete foundations compared to the stiffness of timber structures allows to neglect differential vertical settlements and their effects on upper structure. This characteristic simplifies the design of timber elements and connections. Non-structural requirements have an important role in design phase of foundation system. Practitioners have to pay particular attention in the design of details, in particular for wall-to-foundation node [1]. They have to adopt some expedients reported in the state of the art to avoid any kind of issue related to durability that can be occurred during the service-life of a timber structure [2,3,4,5,6,7]. In order to avoid unexpected capillary rise of water from the ground, the foundations system has to be design as a waterproof barrier between the ground and the wooden wall. Usually, concrete beams were casted in situ above the foundation slab along perimeter wall panels. Levelling and alignment of the beam elements are the most critical issue due to imprecision of casted concrete slab and to the presence of the steel rebars protruding from the slab. Recently, several companies proposed different timber-to-foundation systems made with aluminium [8], or reinforced concrete [9,10], aimed to solve those critical aspects. This paper present results of an experimental campaign conducted on an innovative "beam type" foundation system (Figure 1) proposed by Canetti et al. [10]. Tests were performed in order to characterize the mechanical behaviour of the foundation system for different configurations of loads. Different widely used typology of timber walls, like Light Frame Timber (LFT) and Cross Laminated Timber (CLT) are suitable for this foundation system. The wide range of width of concrete beams make eligible the use of bio-based material walls that exhibit a large thickness compared to traditional systems or wall with diagonal boards that combined traditional technology and circular economy.

Figure 1: *Prefabricated concrete beam-foundation element example of use on construction-site (CLT and LFT walls)*

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[1] Davide Canetti, Alpeas, Italy, davide.canetti@alpeas.it
[2] Francesca Paoloni, Architect, Italy, fra.paoloni@gmail.com
[3] Riccardo Fanti, Institute of Bioeconomy - National Research Council of Italy (CNR-IBE), Italy, riccardo.fanti@ibe.cnr.it
[4] Alessandro Setti, Institute of Bioeconomy - National Research Council of Italy (CNR-IBE), Italy, alessandro.setti@ibe.cnr.it
[5] Andrea Polastri, Institute of Bioeconomy - National Research Council of Italy (CNR-IBE), Italy, andrea.polastri@ibe.cnr.it
[6] Fabrizio Tamburini, Tamburini Prefabbricati, Italy, info@tamburiniprefabbricati.it

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2 PREFABRICATED CONRETE BEAM FOUNDATION SYSTEM

The system here illustrated is composed by reinforced SCC concrete (Self Compacting Concrete) linear elements with rectangular section. The prefabricated beam is intended to be used as a base for structural/non-structural timber walls; in particular, the foundation was optimized for LFT and CLT structures.

The foundation elements are made in a prefabrication plant following specific production controls, proper formworks were designed in order to obtain the required rectangular sections, with a width from 120mm to 200mm and a depth up to 380mm; the maximum length is equal to 4000mm. Thanks to the special adjustable metal formwork and the use of self-compacting concrete, it is possible to create linear elements almost totally free of geometric defects (the expected production tolerances are +/- 6 mm on nominal dimensions) so to guarantee an excellent result during the assembly at the construction site.

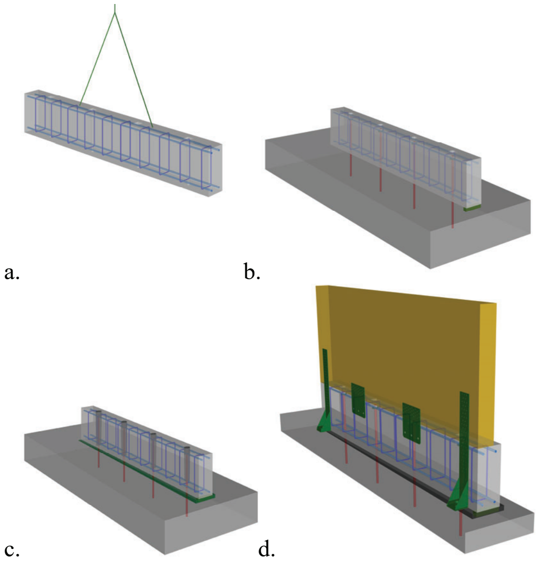

Figure 2: *on site construction phases: a) lifting; b) levelling and anchoring; c) filling vertical cones and horizontal gap with repair mortar; d) connecting timber wall to the prefabricated system*

The design, production and on site operations takes place according to the following procedures: typically, the design phase starts with the executive structural design plant; in particular, it is necessary to properly define the ground floor walls of the timber building and the associated maximum vertical forces per unit length and the maximum horizontal shear forces per unit length along the shear-wall. The designer develops a detailed executive plan of the foundation, standard prefabricated beam modules with a length equal to 2000mm are adopted; where is not possible sub-modules and non-standard elements are designed.

Afterwards, designers perform a structural verification of the anchor bar that connect the prefabricated modules to the foundation slab, a minimum longitudinal reinforcement have to be provided.

Last step is the development of production drawings and a clear assembly diagram to be use on construction site. All the indications needed for handling and storage on site are given through installation tables.

The production of the elements at the concrete prefabrication plant has to consider the installation of the bushings for lifting them. Concrete cubes for product quality control have to be stored and tested.

Once the prefabricated concrete beam modules are on the construction site have to be positioned through the appropriate lifting points, which are already set up in each element (Figure 2a).

Foundation beams are then levelled using proper metal plates and anchored (glued with proper epoxy resin) to the foundation slab with B450C (16mm diameter) reinforcing bar (Figure 2b).

The final operation consists in casting special repair mortar in order to fill all the gap between the prefabricated elements and the foundation, followed by the filling of the upper cones (Figure 2c) using high compressive strength and anti-shrinkage pourable mortar. When the prefabricated elements are properly fixed to foundation timber walls can be installed above the concrete beams and anchored with steel plates to the beam against shear loads and directly to the foundation slab with hold-downs to prevent the rigid rotation (Figure 2d). Steel plates and hold-downs are nailed or screwed to the timber walls and connected to beams and slab by means of threaded rods.

The structural elements are made according to EN13225:2013 [11]. The concrete beam presents several holes with conical shape along its length centred at the middle of the element's width for insertion of vertical anchor bars: lower diameter of 25mm and a flaring with an inclination of 1° towards the outside of the hole. The number of holes has to be designed by the practitioner: equally spaced holes at 500mm are typically adopted.

The concrete cover to be used is 30mm for an ordinary carbonation class XC2, with concrete cover factory control and a nominal life of 50 years. The main geometrical and mechanical properties of prefabricated concrete beam are reported in Table 1.

Table 1: *Geometrical/mechanical properties of concrete beam*

Prefabricated concrete beam	
Concrete	C30/37
Consistency class	SCC
Exposure class	XC2
w/c ratio	0,40
Calcareous filler [kg/m^3]	148
Sand 0-4 [kg/m^3]	245
Gravel 5,6-16 [kg/m^3]	1311

Figure 3 reports some technical details of the prefabricated concrete beam, construction site views in order to show the technological aspects and the construction phases showed in Figure 2, of the proposed systems, that were developed to ease a simple and precise assembling of the foundation beam and consequently of the timber walls placed on it.

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Figure 3: *on site construction phases: levelling and anchoring (top picture); placing the CLT walls on the top of the prefabricated beams (central picture); connecting timber wall to the prefabricated system (bottom picture)*

3 EXPERIMENTAL CAMPAIGN

An experimental campaign with three series of monotonic tests for a total number of 10 test typologies were carried out in order to completely characterized the mechanical behaviour of the prefabricated concrete foundation system. The prefabricated concrete beam tested specimens are characterized by a depth equal to 350mm, width from 120 to 160mm and length from 560 to 1300mm. The concrete elements are reinforced either with steel bars and hoops or with steel fibers.

Different configurations were studied by means of specific tests. The experimental tests were designed and performed on: anchor system of the beam element in tensile configuration (Figure 4a), beam-to-slab connection in shear configuration (Figure 4b) and panel-to-beam (CLT-to-concrete) connection (Figure 4c).

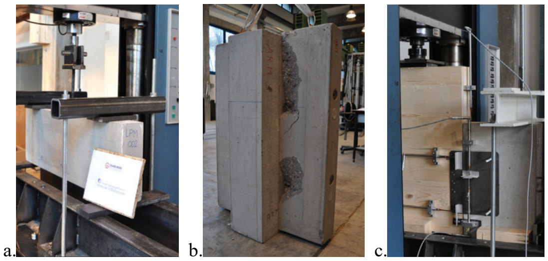

Figure 4: *Prefabricated beam foundation element: a) tensile test; b) specimen after the shear test; c) wall panel-to-beam connection test.*

The tensile tests on anchor system of beam element were carried out according to setup in Figure 4a. Beam elements are characterized by a depth equal to 350mm, width equal to 120mm and a length equal to 1000mm. The single rebar that protrude from the upper surface of the concrete element is fixed to the testing machine in order to transfer the tensile load (Figure 5a).

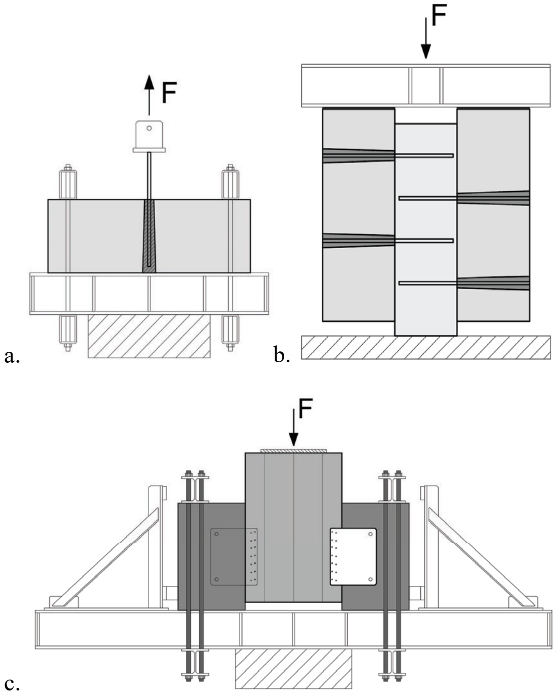

Figure 5: *Test setup: a) anchor system of beam element tensile test; b) beam-to-slab connection shear test; c) panel-to-beam connection shear test*

The element is held down through two rectangular steel profiles. Two different typologies of specimens were tested: beam element reinforced either with steel bars or with steel fibers, according to Table 2. Two tests for each configuration were carried out.

Table 2: *Configurations of anchor system specimens*

ID	test	width [mm]	anchor	d [mm]	reinforcement	n° [-]
1	tensile	120	rebar	16	rebars/hoops	2
2	tensile	120	rebar	16	fibers	2

The beam-to-slab connection specimens were tested according to setup in Figure 4b: two beam elements are fixed (one at each side) of the central concrete element (slab) through two rebars with a spacing equal to 500mm. Beam elements are characterized by a depth equal to 350mm, width from 120 to 160mm and a length equal to 1300mm. The compression load is applied to the two beam elements by a hydraulic jack through a rigid steel beam, as shown in Figure 5b. The tested configurations are reported in Table 3.

Table 3: *Configurations of beam-to-slab connection specimens*

ID	test	width [mm]	anchor	d [mm]	reinforcement	n° [-]
3	shear	120	rebar	16	rebars/hoops	2
4	shear	120	rebar	16	fibers	2
5	shear	160	rebar	16	rebars/hoops	2
6	shear	160	rebar	16	fibers	2

The panel-to-beam (CLT-to-concrete) connection specimens were tested according to setup in Figure 4c. A compression load is applied by the testing machine to a 5-layer 120mm thick CLT panel (Figure 5c). Two steel plates connect the CLT panel to the two concrete beam elements: the connection plates are placed at the opposite face of the central element. Steel plates are nailed to the panel through fourteen 4x60mm Anker nails and anchored with two 8.8 threaded bars in concrete beam (in this case study the concrete elements are reinforced with fibers). The bars are fixed to the concrete beam with epoxy resin or screwed in special threaded bushing placed during the casting phase (at the production site). The tested configurations details are reported in Table 4. One test for each configuration is carried out.

Table 4: *Configurations of wall panel-to-beam connection specimens*

ID	test	width [mm]	reinforcement	threaded bar fixed system	n° [-]
7	shear	120	fibers	steel bushing	1
8	shear	120	fibers	epoxy resin	1
9	shear	160	fibers	epoxy resin	1
10	shear	160	fibers	steel bushing	1

Tests were performed according to EN26891:1991 [12]. The load rate was not greater than 0,2 mm/s and the maximum load was reached in 300 ± 120 s in all tests.

Results of the three series of monotonic test are reported in Table 5 in terms of mode of failure, stiffness k, maximum force F_{max} and corresponding displacement v_{max}.

Table 5: *Mechanical parameters and mode of failure of the tested specimens*

ID	test	k [kN/mm]	F_{max} [kN]	v_{max} [mm]	mode of failure
1	tensile	-*	59,6	-*	concrete cone combined to pull-out failure
2	tensile	-*	96,9	-*	concrete cone combined to pull-out failure
3	shear	32,7	127,4	29,2	large deformations**
4	shear	52,6	177,5	22,1	limit load***
5	shear	49,9	162,9	28,7	large deformations**
6	shear	43,4	172,1	15,4	limit load***
7	shear	9,6	50,9	14,6	steel-to-timber connection
8	shear	6,9	46,2	13,5	steel-to-timber connection
9	shear	9,7	54,2	14,3	steel-to-timber connection
10	shear	6,5	57,2	15,7	steel-to-timber connection

*displacements were not measured in this test configuration
**test was interrupted due to large deformations (>30mm)
***test was interrupted due to limit load of the hydraulic jack (>400kN)

For the shear tests the mechanical parameters are referred to a single shear plane (i.e. for single concrete beam in beam-to-slab tests and for a single steel plate in panel-to-beam tests). In the cases where two tests are carried out in the same configuration, the average values are reported.

The tensile tests show the same failure mode: the pull-out of rebar combined with the formation of a concrete cone is observed (Figure 6a). In tensile tests the displacement is measured through the testing machine.

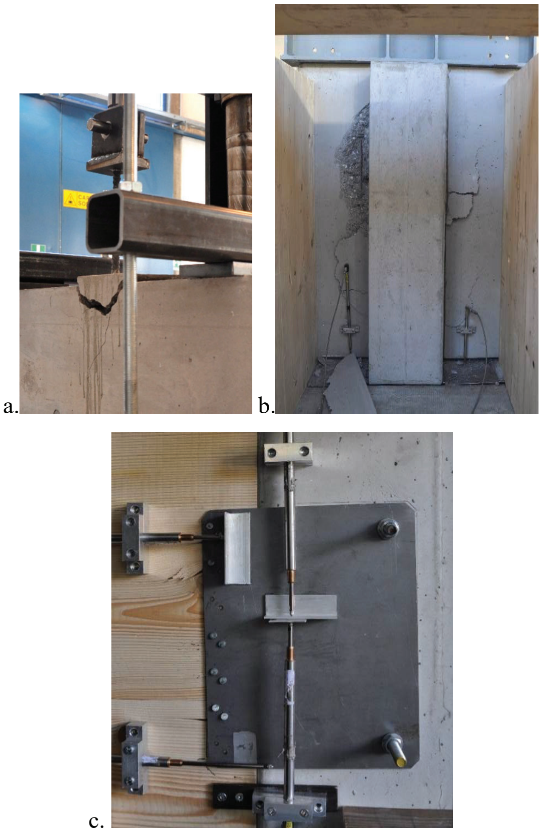

Figure 6: *Failure modes: a) tensile test; b) beam-to-slab connection shear test; c) panel-to-beam connection shear test*

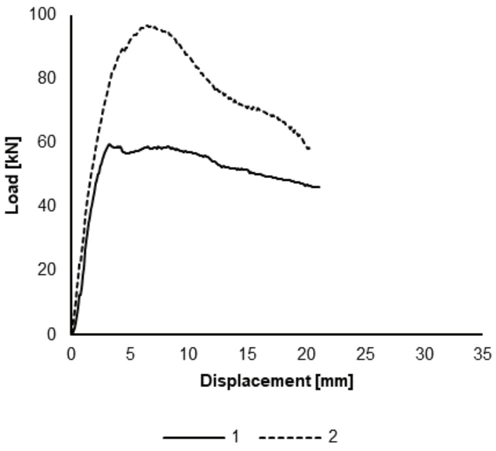

Figure 7: *Tensile tests results*

The fiber-reinforcement beam specimens showed a higher strength and similar value of stiffness compared to rebar reinforcement. The load-displacement curves for both configurations are reported in Figure 7: as mentioned above, the mean values were obtained from two specimens of the same typology.

The shear tests on beam-to-slab connection are interrupted for two different reasons: in case of concrete beam reinforced with rebars tests are interrupted at 30mm of displacement (consistent with the provisions reported in EN12512:2005 [13]), whereas, in case of fiber-reinforcement tests are interrupted due to the reaching of load limit of the hydraulic jack (applied load shouldn't exceed 400 kN). At the end of the tests, in both cases, cracks and spalling of concrete near connections are observed, as shown in Figure 4b. A comparison in terms of load-displacement curves is reported in Figure 8 (mean displacements were obtained from the four LVDTs measurements). After reaching the yielding point (approximately at 5mm of displacement for all specimens) the load in fiber-reinforced specimens rapidly increase until the load limit of the hydraulic jack while slowly increase in other specimens (reinforced with steel bars) until 30 mm of displacement.

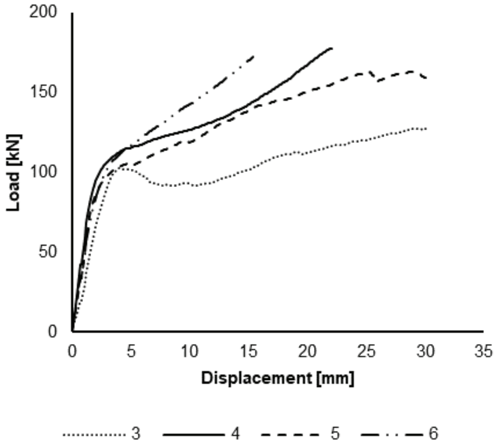

Figure 8: *Shear tests results: beam-to-slab connection*

The shear test on panel-to-beam (CLT-to-concrete) connection failed due to reaching the steel-to-timber connection (nails) strength, as shown in Figure 6c. Rotation of the steel plate and cracks in CLT panels in the nailed areas are observed. The experimental values of maximum strength F_{max} and corresponding displacement v_{max} are approximately the same for each specimen, due to the same failure mode registered in the tests. The values of stiffness of steel-to-timber connection are similar to the values obtained in other experimental campaigns. The width of the beam element (120mm or 160mm) and the different fixing systems, used to anchor the steel threaded bars, seems have no influence on the mechanical behaviour of the tested specimens. No failures are observed in the beam elements. A comparison between the load-displacement curves of the four tested specimens is reported in Figure 9.

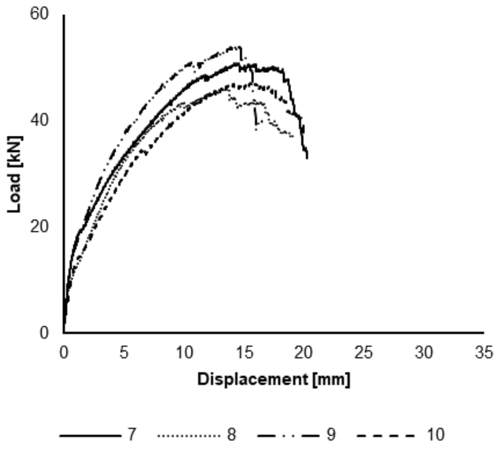

Figure 9: *Shear tests results: wall panel-to-beam connection*

4 CONCLUSION

The paper presents an innovative concrete prefabricated beam foundation system aimed to mitigate the risk of durability issues in timber elements and to ease the on-site building procedure. In particular, results obtained from an experimental campaign are presented and discussed. Tensile tests on anchor system, shear test on beam-to-slab (concrete-to-concrete) and on panel-to-beam (CLT-to-concrete) connection are reported in this paper. The tensile tests on anchor system showed a mode of failure due to the pull-out of rebar combined with the formation of a concrete cone. Beams reinforced with fibers exhibited higher strength than beams reinforced with rebars. The shear tests on beam-to-slab connection show significant strength and stiffness; no failures were observed in case of beams reinforced with steel fibers (the limit load of hydraulic jack is 400kN). Beams reinforced with rebars also exhibited high level of strength and stiffness but less than beams with steel fibers, due to the local cracks and large zone of spalling of concrete cover; after the yielding point, the load slowly increase until the limit displacement, equal to 30mm, where tests were interrupted. The panel-to-beam connection specimens were characterized by a steel-to-timber nail failure mode. Yielding of nails allowed to reach a ductile failure mode. No cracks near the threated bars were observed. Regardless of the width of concrete element no failures were observed in beams. The prefabricated concrete beam presented in this paper can be considered a valuable foundation system developed to guarantee the durability of timber structures. A simple and fast assembling system for timber walls on the construction site, at the foundation level, is ensured through these elements.

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