Maintenance and Structural Check of an All FRP Pultruded Construction

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Abstract. The proposed research focused on the maintenance and structural check of the first all FRP (Fiber reinforced polymer) pultruded construction built in Italy in the 2018. The proposed steps have been mainly in the frame of the joint's efficiency evaluation from the local point of view, and in that of visual inspection from a general point of view. By the way, the joint made by bolts are the more potential weak part in these type of constructions. The construction – all FRP made unless steel bolt – has been the consequence of a specific call and is built in the Iuav University Campus in Venice. The structural check is developed through cyclic in situ analysis of the joint bolted efficiency, specifically by means moment toque value applied evaluation and visual damage detection also considering closed formulas already available both for all FRP bolted joints and similar ones as well as connections made by steel and wood. Bolt monitoring is managed by means of a controlled tightening torque wrench which is used to detect the tightening torque for each bolt in the structure. To calculate the friction coefficient used, it was chosen to use the experimental formula on the determination of the μ. For the research, it was decided to use two different friction coefficients to calculate the tightening of the knots. The final aim of the research is to show the results of the structural controls and discussed in the framework of the general performances foreseen for all FRP structures.

Keywords: Maintenance · All FRP structures · Bolted connections · Pultruded elements · Hollow profiles

1 Introduction

The long-term sustainability of buildings is today a fundamental objective for architecture, engineering and construction. This applies to both new construction, recovery, reuse and structural strengthening of historic buildings. The world of fiber-reinforced polymers (FRP) allows structural designers to achieve the goal of long-term sustainability in a wide range of applications; this is due to the mechanical characteristics of the materials, the reversibility and durability of the works, the simple and quick construction for the application (Boscato and Russo 2013). This is evident in the main fields of application in Italy: we can divide them into new constructions whose elements are identified with pultruded profiles; the repair, strengthening and seismic rehabilitation of concrete and masonry structures with FRP sheets and plates; structural hybrid, such as

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glass beams - FRP (Bedon and Louter 2018, Speranzini and Agnetti 2015, Neto et al. 2015, Bedon and Louter 2017).

Within these fields, the most common types of application are hybrid concrete-FRP constructions (bridges, viaducts, etc.) and structural strengthening of masonry structures (mainly historical) for protection against earthquake damage (Bank 2006). These precious innovations achieved with new materials demonstrate the good compatibility between FRP composites and fragile porous materials generally subjected to compression stresses.

Within this general framework, the possibility of strengthening with pultruded FRP profiles (PFRP) has not yet been explored; some case studies (especially in Italy) have been created which present autonomous structures or PFRP substructures inside historic masonry buildings (Qureshi et al. 2015).

In the figures below it is possible to see the use of profiles for a walkway inside an archaeological park. The same profiles can also be used for temporary coverage on the post-earthquake construction site. The last image shows the Glass House, a project created in collaboration with the IUAV and made interaction with FRP pultruded (Sciarretta et al. 2018) (Fig. 1a,1b,1c).

These cases do not concern the properly understood structural strengthening of masonry structures with members or PFRP systems.

a) b) c)

Fig. 1. Exemples of FRP structures, a) temporary walkway, b) post-earthquake coverage, c) Glass-House.

Currently, trusses or frames, in steel or other metallic materials, are a solution to increase overall the strength of existing structures against seismic actions (Mottram and Turvey 1998). They can be placed next to existing load-bearing walls or portals and must be connected to the floor bridges. The geometry of the frame must take into account the openings of doors and windows. This type of solution allows the frames to occupy all of the loads and transfer them autonomously to the foundations, therefore it is attractive whenever the existing load-bearing members show poor shear behavior. In the case of historic buildings, the reinforcement arrangements must meet the aesthetic and integrity requirements of the decoration (Boscato et al. 2014). For this reason, steel frames, internal or external, are a suitable solution for renovating masonry with low surface conservation requirements, such as towers (Fig. 2) (Sciarretta and Russo 2019).

These well-known structural systems reinforcement solutions could bring new benefits by conceiving them with pultruded FRP materials (Owens and Moore 1992). From the point of view of sustainability, costs, maintenance and the weight of steel, they can

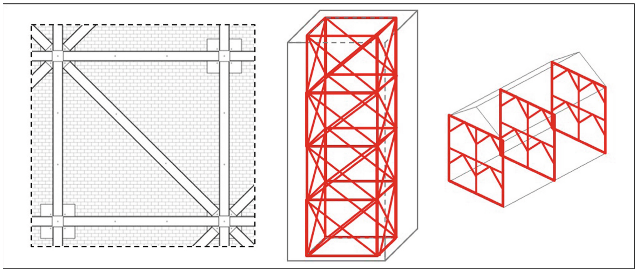

Fig. 2. Type of reinforcement proposed.

become critical problems. In fact, FRP technology maintains high strength, quick and simple assemblies and removability of the metal structure, but adds the advantages of low weight and higher cost-effectiveness thanks to the low maintenance requirements (Turvey 2000). On the other hand, the potential disadvantages of PFRP can relate to the fire performance and high shear deformability. As some research has shown, PFRP structures could achieve the same performance levels as steel (Casalegno and Russo 2015).

The research aims to facilitate the structural design of the PFRP. A particular focus is placed on the connections between FRP profiles and steel bolts (Mottram 2004). These types of connection (currently not standardized) at the expense of gluing, have a good level of reversibility and non-invasiveness, since they are punctual and the elements can be dismantled and reassembled very easily.

2 Structural Aspects

The structure is made completely of pultruded FRP box profiles and steel bolts. The elevated structure of the pavilion has a rectangular mesh size of 8500 mm × 11450 mm.

The C profile that characterizes the entire structure with a length of 8500 mm, is not a single profile, but is the result of the union of a beam with a length of 6000 mm and the other part with a length of 2500 mm. The vertical elements are box-shaped profiles made with 1250 mm × 4000 mm pultruded panels placed at a middle distance of 1250 mm. These panels are connected in foundation to a FRP stiffener structure fixed to a double support board with a total thickness of 80 mm (Fig. 3).

At floor level, the stiffener structure is made of two C profiles with dimensions 2000 mm × 600 mm × 100 mm fixed to the vertical panels. These profiles are the support surface of the paving slabs. To increase the stiffness orthogonal to the slabs, there are connections made up of 2 C profileswith dimensions of 2000 mm × 600 mm × 100 mm near each slab between the various portals. The roof also consists of two profiles C 2000 mm × 600 mm × 100 mm similar to those indicated on the flooring, on which the pannels that have the function of covering are fixed. The bracing of the structure is made with angular profiles 1000 mm × 1000 mm × 80 mm, fixed to the upper wings of the pavilion (Fig. 4a,4b).

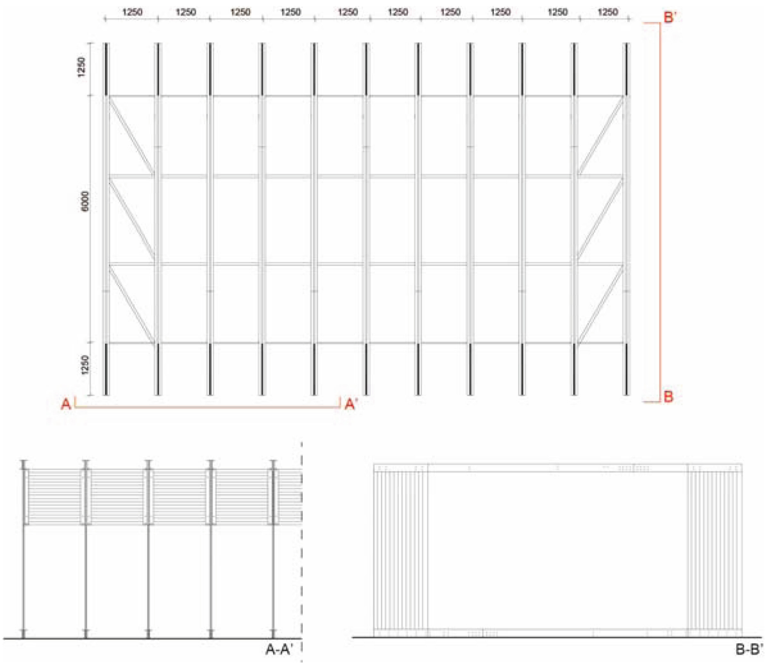

Fig. 3. Glass house, plan and prospects

a) b)

Fig. 4. Glass house, a) side view, b) view from top.

3 Joint Design

Each connection inside the pavilion is made up of bolts whose dimensions vary between M12 and M16. The nuts and bolts used are in AISI 304 stainless steel, A2 quality austenitic steel, strength class 70, breaking load $\geq$ 700 N/mm^2, in accordance with UNI EN ISO 3506. The screws used are fully threaded DIN 933, the nuts are medium hexagons DIN 934, with narrow washers DIN 125 A. All components are in AISI 304 steel. A 30 mm washer is placed between the bolt and the FRP profile.

In the central part of the profiles is placed a hollow box, also in FRP with dimensions of 25 mm.

The connections are attributable to five types replicated within the structure as visible from the figure below (Fig. 5a,5b,5c,5d,5e). Connections *a* and *b* are used to connect the vertical panels to the two C beams; connection *c* is used on the roof to connect the bracing, it is a connection that uses an M12 bolt with a shorter length than the other bolts, as it directly connects two C-profiles; connections *d* and *e* connect the vertical panels with the suspended lateral bracing, this type also has hallow box profiles in the central part. The holes of the pavilion connections have a size of 15 mm, the distance between them varies depending on the location of the connection. The holes of type A connections located at the base of the pavilion have a distance between them of 250 mm; the holes of type B located at the top of the pavilion are grouped in 2 pairs that have a distance between them of 750 mm (Fig. 6).

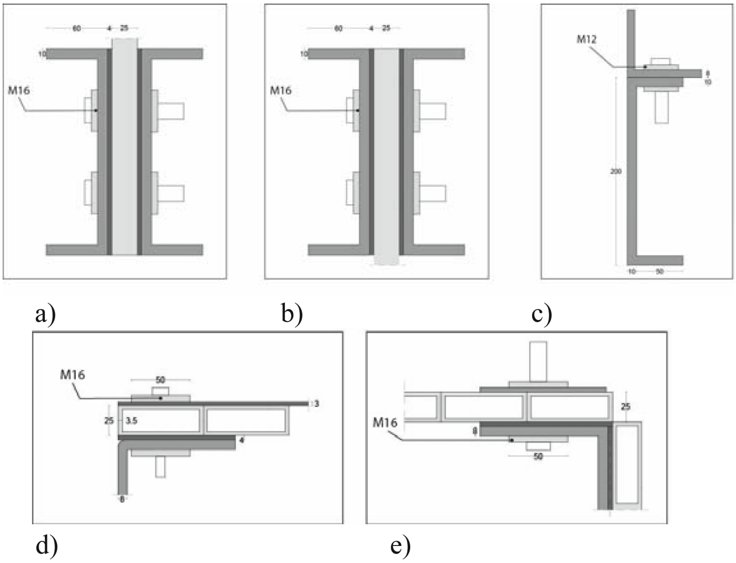

Fig. 5. Pavilion connections, a) base connections, b) connection to the top, c) bracing connection, d)bracing-wall connection, e)connections of braced walls. All unit of measure are in mm.

4 Tightening Test

It was decided to monitor the tightening torques of the various nodes with a controlled tightening torque wrench (Fig. 7). The wrench used is EXPERT E100108, compliant with UNI EN ISO 6789 with a tightening torque that reaches 200 Nm.

The values of the individual bolts were monitored in the assembly phase, 8 months later and 19 months after assembly. During assembly, the tightening bolts with tightening

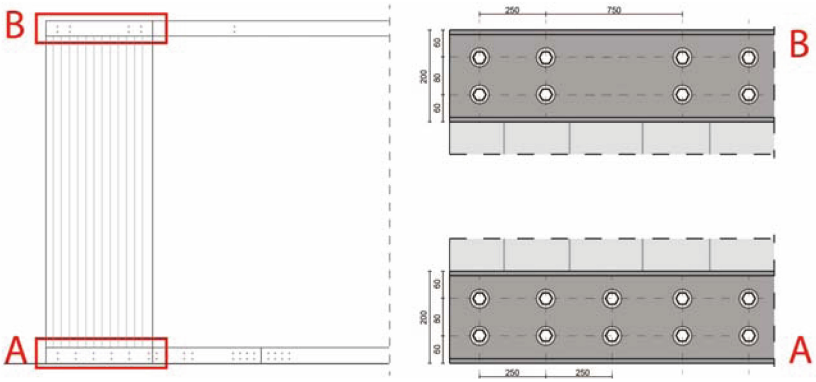

Fig. 6. Pavilion connections, bolts distance.

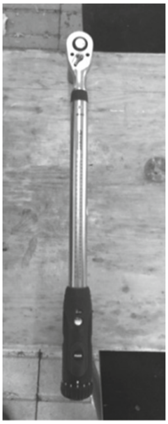

Fig. 7. Torque wrench with controlled tightening.

had been tightened with values of tightening torques for steel and calculated according to the NTC 2018 and DM 17.01.18 (Eq. 1)

$$T_{S(c)} = \mu \times \mathrm{Ns} \times \mathrm{d} \tag{1}$$

that employs the symbolism already used, where $Ts_{(c)}$ is tightening torque calculated, μ is the friction coefficient estabilished from UNI EN ISO 3506, *Ns* is calculated in according to the NTC 2018 and the value, *d* is the bolt diameter.

The friction coefficient used are $\mu = 0.37$ for M16 bolts and $\mu = 0.38$ for M12 bolts. This value is conservatively high and, during assembly, the value used for tightening is the result to be much lower than that calculated (Table 1).

During the first test carried out 8 months after assembly, all the tightening torques of the pavilion were checked. It was verified that all almost all the nodes had lost the initial tightening value.

It was chosen to recalculate the torque to be used inside the pavilion. The value of the coefficient of friction used was taken from one of the few μ present in the literature

Table 1. Values tightening torques of the pavilion nodes

Pavilion connection	Bolt diameter (mm)	Washer diameter (mm)	Slip load Ns (kN)	μ	Torque $T_{S(c)}$ (kNmm)
A	16	30	16.3	0.37	96.5
B	16	30	7.8	0.37	46.1
C	12	30	10.9	0.38	49.7
D	16	50	9.2	0.37	54.4
E	16	30	15.3	0.37	90.5

(Mottram et al. 2004). From tests carried out in the laboratory, the bolt tightening torques were closed in the laboratory and their values were measured by strain gauges. Following the test, the calculated initial values are actually reduced by 20%.

For M12 bolting the frictional force is therefore 0.38 kN per kNmm and for the M16 bolting it is 0.22 kN per kNmm. The approximate coefficient of friction for PFRP on PFRP is therefore *(0.5x0.38)/(2x0.44)* = 0.22 from the M12 bolting tests, and *(0.5x0.22)/(2x0.40)* = 0.14 from the less reliable M16 tests (Table 2) (Fig. 8).

A coefficient of 0.2 is typical of advanced polymeric composites on steel and at the lower bound of the range (0.2 to 0.3) for dry (non lubricated) steel (Kulak et al. 2001).

Table 2. Tightening torques calculated with the new friction coefficient

Pavilion connection	Bolt diameter (mm)	Washer diameter (mm)	Slip load Ns (kN)	μ(e)	Torque $T_{S(c)}$(kNmm)
A	16	30	16.3	0.14	36.5
B	16	30	7.8	0.14	17.4
C	12	30	10.9	0.22	28.7
D	16	50	9.2	0.14	20.6
E	16	30	15.3	0.14	34.2

Starting from the standard formula of the calculation of the tightening torque, we used the inverse formula for the calculation of the friction coefficient. For the friction coefficient the experimental formula was used which divides the tightening torque applied by the preload multiplied by the diameter of the bolts (Eq. 2)

$$\mu_{(e)} = \frac{T_{S(e)}}{N_S \times d} \tag{2}$$

Where $\mu_{(e)}$ is μ is the experimental friction coefficient, $T_{S(e)}$ is tightening torque experimental (the value was measured on each type of bolt with the torque wrench), slip load and bolt diameter are the same of Eq. 1.

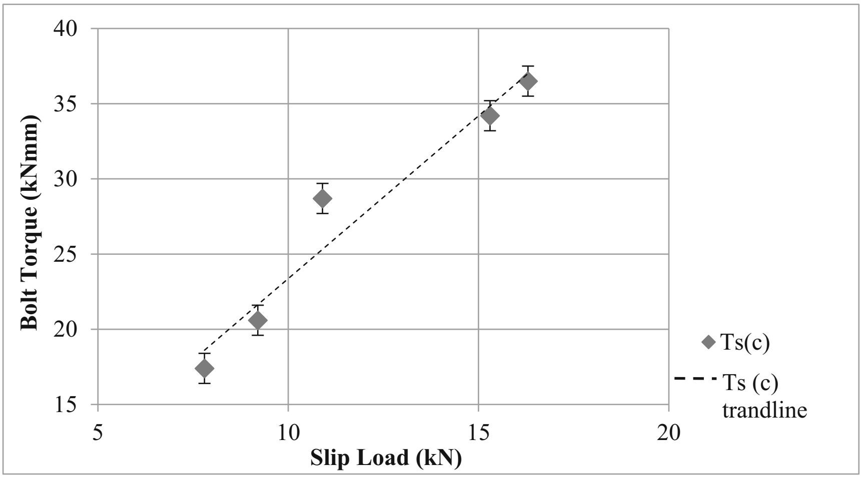

Fig. 8. Load-slip results with scatter bars and trendlines for Ts(c)

5 Discussion

The experimental formula indicated above Eq. 2 was used to calculate the new tightening torques for the five types of knots present in the structure, all the knots were tightened with a value much lower than the tightening torques used for the first assembly. For all the nodes it was chosen to use a dry tightening, in order to make the pavilion totally removable and reassemblable.

During verification, when tightening the bolts with the torque wrench, it was not possible to close the bolt up to the calculated torque, as it was aware of the acoustic emission. As from the studies done, we know that the acoustic emission is closely related to the damage, we preferred not to arrive at the calculated Nm to avoid causing damage in the profile. However, using the new friction coefficient, the values of the tightening torques are much lower than those initially calculated with the friction coefficient used for steel. It can be seen from the table below (Table 3) that not all the tightening torques applied correspond to those calculated but, the values applied differ by 10% with respect to those calculated (Fig. 9).

The second monitoring of the nodes took place 19 months after assembly. Also during this phase the knots were checked with the same controlled tightening torque wrench. All the knots, contrary to what was verified the first time, where the tightening torques had almost entirely lost the tightening torque. At a distance of 11 months from the first monitoring, all the tightening torques tightened with the new values calculated with the experimental formula were verified (Table 4).

The values of the torque loss were the result of an average of the measurements found on all the bolts monitored inside the pavilion. In the image below are highlighted in blue and orange the connections of type B and E that result to have lost 10% of the tightening torque, in red the typology C that turns out to have lost 8% of the tightening torque (Figs. 10a,10b).

Table 3. Tightening torques calculated with the new friction coefficient

Pavilion connection	Bolt diameter (mm)	Washer diameter (mm)	Slip load Ns (kN)	μ(e)	Torque calculated $T_{S(c)}$(kNmm)	Torque applicated $T_{S(e)}$(kNmm)
A	16	30	16.3	0.14	36.5	38.0
B	16	30	7.8	0.14	17.4	22.0
C	12	30	10.9	0.22	28.7	38.0
D	16	50	9.2	0.14	20.6	20.0
E	16	30	15.3	0.14	34.2	32.0

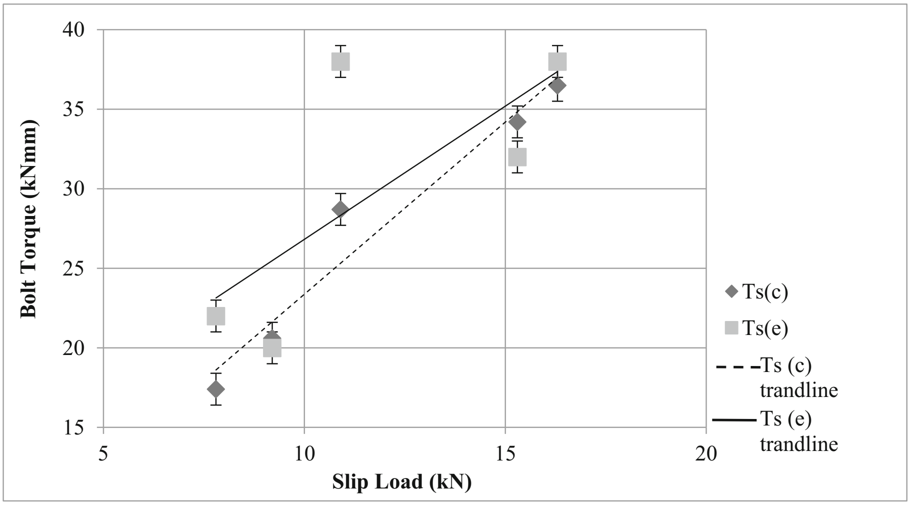

Fig. 9. Load-slip results with scatter bars and trendline for Ts(c) and Ts(e)

Table 4. Summary table of tightening torques

Pavilion connection	Torque calculated $T_{S(c)}$(kNmm) $\mu = 0.37$	$T_{S(c)}$(kNmm) $\mu = 0.38$	Torque calculated $T_{S(e)}$(kNmm) $\mu = 0.14$	$T_{S(e)}$(kNmm) $\mu = 0.22$	Torque applicated (kNmm)	Loss of tightening torque
A	96.5		36.5		38.0	
B	46.1		17.4		22.0	10%
C		49.7		28.7	38.0	8%
D	54.4		20.6		20.0	
E	90.5		34.2		32.0	10%

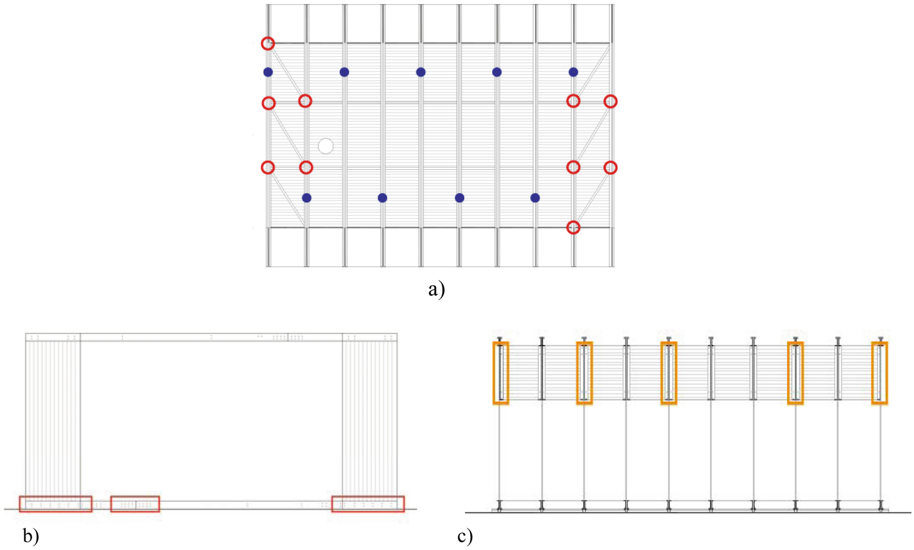

Fig. 10. Glass House a) planimetry of covers with B and C connections, b) later view with node A, c) prospect with node E and D.

Using the experimental formula (Eq. 2) and the values found during the monitoring of the nodes, we can obtain numerically the value of the coefficient of friction to be applied to the nodes present in the pavilion (Table 5).

Table 5. μ Experimental value of μ calculated with Eq. 2

Pavilion connection	Bolt diameter (mm)	Slip load Ns (kN)	Torque $T_{S(e)}$(kNmm)	$\mu_{(e)}$
A	16	16.3	38.0	0.14
B	16	7.8	22.0	0.17
C	12	10.9	38.0	0.29
D	16	9.2	20.0	0.13
E	16	15.3	32.0	0.13

From the correspondence between the calculated values and those applied, the veracity of the formula used derives. The graph below illustrates the values of amortization pairs in relation to the friction coefficient, calculated with the use of Eq. 1 (Fig. 11). From the graph it is possible to notice how the nodes A and E, which have a very similar value for preload, have a very similar value as a clamping torque. The same thing happens for nodes B, C, D.

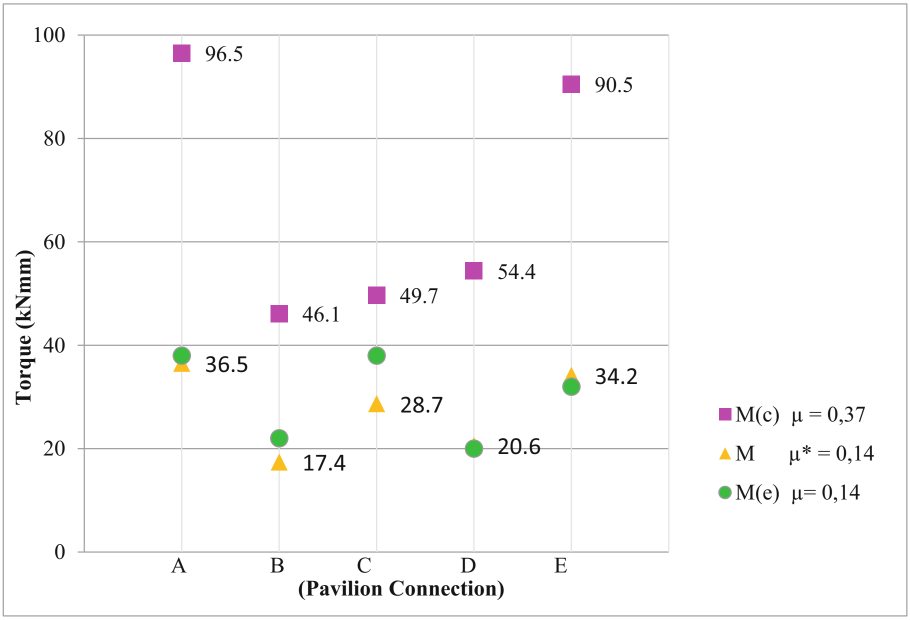

Fig. 11. Summary Graphic of Ts(c) calculated

6 Conclusion

The final aim of the research is to show the results of the structural controls and discussed in the framework of the general performances foreseen for all FRP structures. The tests aim to fill the regulatory vacuum on the dry tightening of structures in fibro-composite material. The research focuses on mechanical sealing in the time of the bolts in particular:

– The regulations on the maintenance of FRP structures, with particular reference to the value of the tightening torque to be applied in the presence of steel bolts, do not answer with clarity on the point;
– The same aspect turns out to be treated and clarified in the presence of bolted connections in metallic carpentry;
– The search, still in progress, evidences altogether a more than discreet mechanical tightness of the bolted connections in their complex;
– In detail, only 2 knots show a reduction of the tightening torque of 10%, and a knot finds a loss of 8%, this found after 11 months;
– Experimental calculation of the coefficient of friction showed a value very close to some values already available in the literature (Mottram);
– In phase of construction of the Glass House all the tightening torques have been of fact applied until the first acoustic emission, therefore with a type of control still of empirical type and not supported from calculations and/or normative specific.

The issue seems worthy of further investigation so that further checks at the limit state on the maximum tightening torque values applicable are also underway through a control of crisis mechanisms with noise emission.

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