Case study involving the use of mechanical couplers for construction of the precast elements on Olympic Tennis Centre for Rio 2016 in Brazil

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***Abstract* – The Rio Olympic Games also celebrated and showcased sport, thanks to the city's stunning setting and a desire to lift event presentation to new heights. Located inside the Barra Olympic Park, the Olympic Tennis Centre was one of the most important venues of the games. The structural project was very hard to design and it was necessary to find engineering solutions with the ability to combine practicality, economy, versatility and quality. Aligned to these concepts, the use of precast elements plays an essential role and has been gaining its fair share of the market; however, the connection of the elements in the structure is still debated amongst engineers and the application of mechanical couplers to connect reinforcing rebar is commonly used as a solution to solve this issue. This paper presents a case study about a threaded coupler application with the main purpose to connect precast beams and columns of the Olympic Tennis Centre in Rio de Janeiro, Brazil. Through the use of previous studies, developing the proper connection specifications for ductility and strength, installation procedures and a high effort in quality control prove that mechanical couplers are an economical alternative for making connections in large precast structures and were well designed and applied on this project.**

1. INTRODUCTION

The Olympic Games Rio 2016 delivered many inspiring athletic achievements that were witnessed and shared by a vast global audience through record-breaking media coverage and unprecedented levels of digital engagement. Against a backdrop of economic, political and social challenges, they also set new standards for legacy planning that have left an important heritage. Events took place at eighteen existing venues (eight of which required some redevelopment), nine new venues built for the Games and seven temporary venues which were removed following the games). Several of the venues are located inside Barra Olympic Park (Fig. 1), including the Olympic Tennis Centre, 5th place in terms of seating capacity, which can hold 10,000 spectators, and it is the focus of this paper.

The beauty of the Rio Olympic Games "hides" the challenges in developing the structural projects of all venues and executing them in time of the scheduled date of the beginning of the Games. These challenges included the application of technologies until then innovative in the Brazilian market, among them, the use of mechanical couplers to connect reinforcing bars of precast elements, an engineering solution which historically provide practicality, economy, versatility and high quality required on many jobs.

Fig. 1: Aerial view of Barra Olympic Park in Rio de Janeiro (www.olympic.org/rio-2016).

Although they have been used worldwide since the 1970s, in Brazil mechanical splices are still underutilized in many projects, even with more attractive costs in mostly situations. The preference for the traditional method by lap splice in the country is due to the lack of culture in the use of mechanical couplers already in the design phase, in addition to the shortage of academic research and professional appeal in Brazil.

This paper explores the good engineering practices and procedures used in the structural design and construction of the Olympic Tennis Centre, addressing the application of couplers for the mechanical splices of the precast concrete elements.

2. CONCEPT OF A PRECAST STRUCTURES CONNECTION

From the point of view of structural behaviour, the presence of connections is what basically differentiates a precast concrete structure from a conventional. Thus, when it is desired to know the behaviour of a precast concrete structure, initially, it is important to know the behaviour of its connections, which are responsible for the redistribution of loads throughout its structure.

In addition, the demand for cleaner and more rational construction with less waste and better use of resources requires the use of standardized components and processes and it is precisely in this context that precast fulfils its essential role. According to Jeremias Junior (2007), particularly in precast concrete crosslinked structures, the overall stability is greatly influenced by the strength and flexural stiffness of the beam-pillar connections and, assuming that most of this type of connection has a partial set-up, design idealizations for perfect articulation or crimping may be inadequate for the determination of second order effects on the structure.

According to Ferreira (1999), the connections of precast elements have a semi-rigid behaviour, meaning initially used in the 1930's, which corresponds to an intermediate behaviour between the rigid nodes and the joints, which can be approximated to one of these situations. Consideration of the deformability of the connections at the ends of the beam members in the structure causes a modification in the stiffness of this member, promoting a redistribution of forces and displacement along the structure.

There are several sorting systems that establish separation limits between these rigidity classes for semi-rigid connections. Bjorhovde et al. (1990) proposed a system based on linear M-θ bi diagram for the moments and the normalized rotations, as shown in Fig. 2.

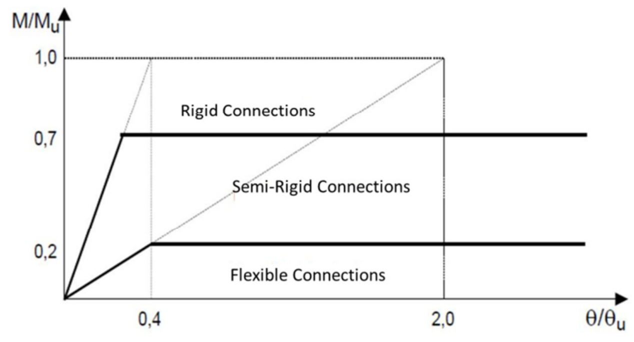

Fig. 2: Classification system for semi-rigid connections, according to Bjohvode et al. (1990).

Ferreira et al. (2002), presents on Tab. 1 a classification system for links in which they are subdivided into five distinct zones. This system is based on the rotation restraint factor (α_R) which takes into account the deformability of the links and is a dimensionless number that relates the rigidity of the connection to the stiffness of the beam that competes with it. For bonds considered semi-rigid this restriction factor varies from 0.15 to 0.85. The coefficient of partial packing (M_E/M_R) represents the ratio of the bending moment at the beam end (M_E) to the perfect bending moment (M_R).

Zones	Restriction Factor (α_R)	Partial Embedment M_E/M_R	Connection Classification
Zone I	$0 \leq \alpha_R <$ 0,14	$0 \leq M_E/M_R$ < 0,20	Articulated (or Flexible)
Zone II	0,14 $\leq \alpha_R$ < 0,40	0,20 $\leq M_E/M_R <$ 0,50	Semi-Rigid with Low Restriction
Zone III	0,40 $\leq \alpha_R$ < 0,67	0,50 $\leq M_E/M_R <$ 0,75	Semi-Rigid with Medium Restriction
Zone IV	0,67 $\leq \alpha_R$ < 0,85	0,75 $\leq M_E/M_R <$ 0,90	Semi-Rigid with High Restriction
Zone V	0,85 $\leq \alpha_R$ < 1,00	0,90 $\leq M_E/M_R <$ 1,00	Perfectly Rigid

Tab 1. : Connections classification on precast concrete structures [Ferreira et al. (2002)].

3. MECHANICAL SPLICES FOR PRECAST STRUCTURES

Rebar splicing corresponds to regions of complex behavior, where stress concentrations occur and which may or may not mobilize displacements and stresses due to the elements connected by them, causing a redistribution of the stress along the overall structure, interfering in the behavior. Thus, it can be categorically stated that the performance of the structural system and the success of its applications are related to the performance of its amendments.

It has been necessary to verify the behavior of the splices in the structural analysis due to the increase in the complexity of the calculations as well as the lack of reliable data. Due to their own behavior, the splices promote the redistribution of the efforts of the elements and also the modification of the final displacements. The failures of certain connections, in the face of certain actions, can cause the structure to collapse. Defects in its execution can lead to stresses that lead to excessive failure or displacement. The equation of the factors that interfere in the behavior of a given connection favors the planning of future experimental studies and is still very useful in the development of criteria for the design and detailing of this connection (Ferreira, 1993).

The connections between precast concrete structures, as the one used on the Olympic Tennis Centre, are one of the most important topics that should be studied by designers. The importance of each one is to make a positive connection in the precast elements to form a structural system capable of resisting all the acting forces as well as, creep, thermal movements, fire, etc. In order to properly develop the structural design, the forces along the structure when subjected to vertical and horizontal loads must be calculated. Also, how the connections are to interact with the elements within the entire structural system must be reviewed.

As already discussed and explored by many authors; and most recently published by CHIARI et al. (2016), there are many advantages in using mechanical splices to provide a reliable and quality assured connection during execution, as listed below:

- Help ease congestion in heavily reinforced sections;
- Improvement structural integrity at the connections;
- Labor and material reduction and the consequent overall cost of the structure;
- Simple and fast installation;
- Reduction of the cracks in concrete;
- It allows the use of the full strength of the reinforcing steel.

Due to the minimum strength requirements of a splice, it is generally assumed in the design that the presence of a mechanical splice or two reinforcing bars does not result in the reduction of a structural strength, stiffness or ductility of the reinforcing steel. Design regulatory standards cover requirements for welded or mechanical splicing, but generally do not specify how to avoid potential weaknesses that can be directly attributed to the specific details or materials of a mechanical splicing.

Design drawings and specifications should clearly define the type(s) of splicing, locations, and technical, as well as their installation methods. Projects should define the specifications of the types of splices and the options available in the market, as well as consider the individual constructability of each one.

Despite being a solution that lacks a "culture acceptance" in Brazilian civil engineering, there are several types of couplers for mechanical splices available in the market. All the of them have applications in many infrastructure jobs, but mainly the greater technical-economic feasibility is related to the large ones, such as hydroelectric plants, buildings, subways, dams and precast structures. For the specific case of the Olympic Tennis Centre in Rio de Janeiro, a taper threaded coupler (Fig. 3) was used to connect important points of the precast structure.

Fig. 3: Taper threaded coupler (ERICO, 2011).

The worldwide demand for mechanical splicing systems is directly or indirectly dependent on a series of requirements and conformities related to standards or specific requirements of a particular project. There are a large number of technical standards related to these systems and the scope of each of them varies according to each region. Since the use of mechanical splicing systems has become common throughout the world, a number of standard-setting committees have been formed with the aim of drafting technical standards and establishing technical parameters and test methods.

Although old and few used by structural design engineers, the Brazilian standard ABNT NBR 8548 (1984) is still used and establishes that the minimum requirements for yield (f_y) and ultimate tensile strength (f_u) for mechanical splices must be the same for the CA 50 steel bar, in other words, 500 MPa and 540 MPa ($108\% f_y$), respectively.

Although not used in this project, the new Brazilian precast standard, ABNT NBR 9062 (2017), was released in March 2017 and brings in its scope three different typologies (Fig. 4) where couplers should be used. Even if the couplers are used in all kinds of jobs worldwide, in Brazil they are only used when there is a real need, especially to connect precast elements. Due to this important detail, ABNT NBR 9062 (2017) came to modify the way the couplers are designed and applied.

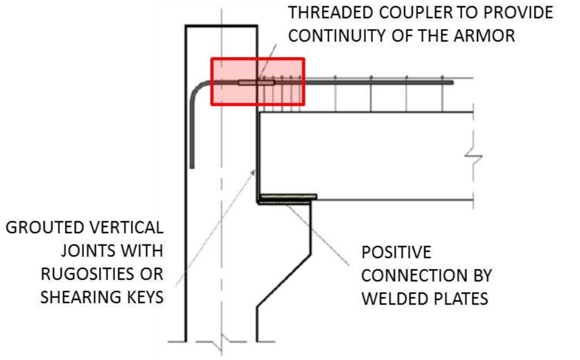

Fig. 4: Adaptation of Typology 4 of ABNT NBR 9062 (2017) detailing threaded couplers to provide continuity of the armor in a beam-column connection.

4. OLYMPIC TENNIS CENTRE STRUCTURAL DESIGN

The project of the Olympic Tennis Centre was designed following a request from the contractor. The Olympic Tennis Arena is a circular arena with a 120-meter diameter and 10,500 sqm of projection area, built for the Olympic and Paralympic Games Rio 2016. With capacity for 10,000 people, its execution was considered as a permanent building incorporating the structure of sports arenas of the city after the Games. Fig. 5 presents and internal view of the Olympic Tennis Centre after conclusion of the jobs.

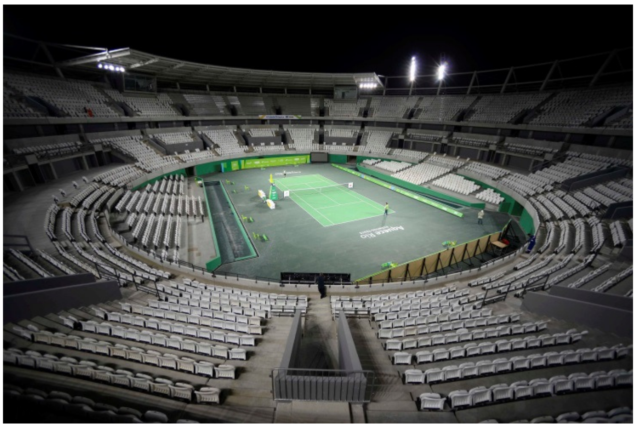

Fig. 5: Internal view of the Olympic Tennis Centre in Rio de Janeiro.

Originally, the executive project was designed by a German company which foresaw a cast-in-place structure with flat slabs in its intermediate levels connected to radial stiffening walls. From there, the stands structure was developed, having as striking structural elements two lines of inclined columns which supported them and their access level in their outer ring. From these columns, Franki cast-in-place concrete piles were adopted as a solution for the metallic latticework bearing base from the cover to the foundation. However, it was analyzed this solution was not practical enough to meet all the project requirements and it was decided to find a new foundation system that would also allow the reduction of the project deadlines.

The adoption of an in-situ construction scheme for a sports arena is not a usual solution nowadays, given the constant search for shorter construction times, rationalization of executive methods and cost reduction, which leads to the fact that most of the sports arenas currently execute them using precast solutions; and the first design would make the entire structure to be fully anchored on all levels during the construction, something impossible to make feasible in this particular case.

Therefore, a precast concrete structure should be developed to meet the needs of the arena as originally designed, without changing the visibility curve, due to all performance studies of quality of use for the people present and the television broadcasting needs that an arena in this type of event has to attend. This means that the in-place structure that had been studied initially and developed for 6 months had changed to a precast structure that respected the same conditions of pavement levels, height, visibility curve and operability. The northwest layout of the stands of the "new version" of the Olympic Tennis Arena design is illustrated at Fig. 6.

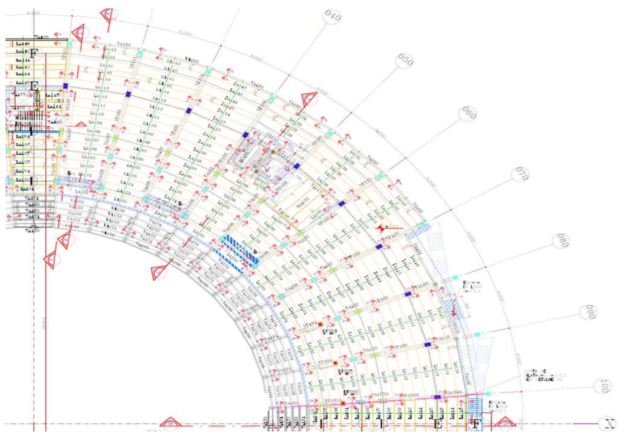

Fig. 6: Northwest layout of the stands of the Olympic Tennis Arena (Monteiro & Gomes Engenheiros Associados).

The entire design of the precast concrete structure was based on the concept that consist of a set of columns, beams and slabs that are interconnected to form a structural system that is capable to support and transfer the vertical and horizontal forces of the floors into the foundation. General design considerations in precast concrete structures include structural system selection, component optimization, service provision (fabrication, transportation and assembly); and special features and other items requiring specifications, as well as aesthetic aspects.

The development of the precast structure would have to be carried out in parallel with the execution of the job, since the deadlines were already in progress and the opening date of the Olympics Games could not be changed. There was also verified an alternative to the foundation system designed (Franki piles), which had already been identified as impractical because of the difficulty in the speed of its execution in the field. Due to the fact that the designer had worked on the concrete and foundation project of the Future Arena (Olympic Stadium of Handball) and structures built for the 2007 Pan-American Games, he used to have a good knowledge of the field conditions, allowing a quick evaluation and definition by the change of the foundations for Continuous Flight Auger (CFA) drilling.

Three were basically the critical points for the reworking of the structural design: the maintenance of the average dimensions of the pieces so that they did not represent changes in the existing designs, the shapes of the inclined columns, whose basic levels of the structure should be maintained without loss of quality in the aspect of stability and last but not least, find a non-interference solution of the first tier of bench in the stands at its lower level so as not to affect the desired visibility curve. In addition to the structural aspects, the concrete volumes of the structure should be kept as close as possible to the original project because the project could not suffer price increases motivated by the change in its executive system.

The gantry structures comprise two main columns lines from which, from the level of access to the stands, one of these lines becomes a inclined element at approximately 30º, on which supported the beams of the stands (Fig. 7). Due to the production and transport processes of the precast structure, these columns needed to be transported and installed in two separate segments.

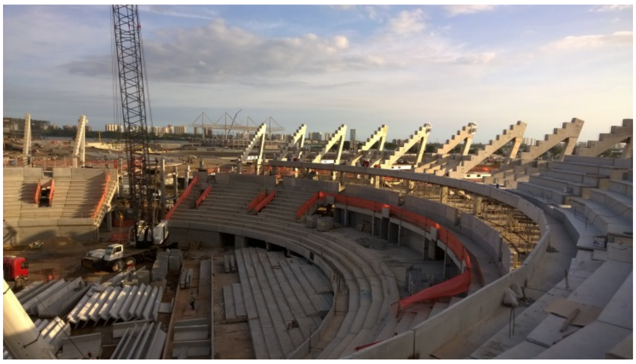

Fig. 7: View of the stands with the columns inclined at 30º.

Since these are the basic premises to be met, it was adopted in the design of the structural solution the execution of semi-rigid connection nodes in order to guarantee the monolithism of the structure after its execution maintaining it with a structural behavior similar to that proposed in the original conception. The connections between precast structures must meet different design and performance criteria, being their primary function is to transfer stress between the interfaces of the precast elements, so that they interact with each other as a single structural system. Due to the complexity of this architectural project, mechanical threaded couplers were considered on the structural design to connect beams and columns of the Olympic Tennis Centre (Fig. 8).

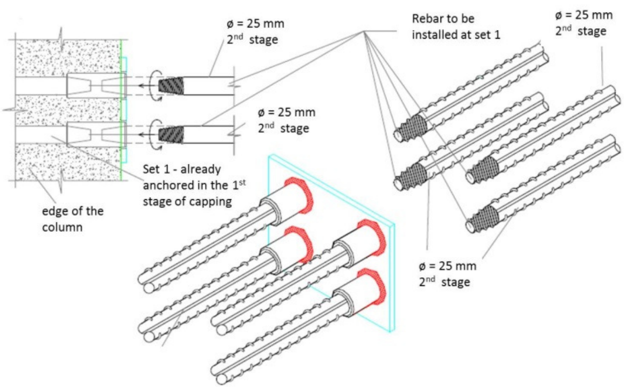

Fig. 8: Detail of the connection by taper threaded couplers designed for Olympic Tennis Centre (Monteiro & Gomes Engenheiros Associados).

The whole structural set was analyzed to the effects of wind, taking into account the conditions of stability in the limit state of use, with levels of vibration of the structures within the comfortable standard to the people, with or without the effect of the wind. Like all structure of this type, a radial tensile stress is generated at its upper end, which tends to open its upper ring. In order to combat this situation, a metallic beam was fixed to the head of the columns (Fig. 9) to balance this effort, in a good example of which structures should be solved as the best option for the necessity that presents itself and not simply by adopting a unique executive system. In this case, the metallic structure was not only the best solution, but also perfectly complemented the precast concrete structure.

Fig. 9: Metallic beam fixed to the head of the columns.

In the case of the interference of the first step level of the internal radial distribution corridor of the stands, it could not have an inferior support, since neither the level nor the lower radial corridor could be modified. The solution was then to create a "flange with side flap" attached to the end of the support beam, making it possible through a 25 mm taper threaded rebar using couplers tied to this beam. It was located below the floor of the subsequent step, and after assembly, these elements were subjected to load tests to ensure total safety of the connection. The results showed that they were able to handle a situation of more than 2 times the design loads.

At the end, in the comparison of the total volumes of the job, the precast structure performed (Fig. 10) presented volume variation 7.5% higher than the original cast-in-place design. This percentage was within the maximum value of 15%, usually acceptable, since it is natural that the precast system has an ever larger volume due to its assembly characteristics.

Fig. 10: External view of the Olympic Tennis Centre arena.

5. CONCLUSION

This paper, based on the prescriptions of the structural design, revealed mechanical splices by threaded couplers are a good alternative for connections in precast concrete structure used in the Olympic Tennis Arena. In addition, the good result of the transposition of solutions was the connection of knots of the structure through the use of those mechanical splices allowed the structure to function as hyperstatic, guaranteeing comfort to the regulars in the face of rigidity of the structure as a whole. Furthermore, couplers minimized congestion of the armature.

It was also observed that the assumptions established during the design of the structural project were determining factors to promote a structural element intact after execution, enabling a very satisfactory final result. Although mechanical couplers have been used for more than 30 years on the international market, the specification of mechanical couplers in Brazilian projects of any size is still a taboo, and much work still needs to be done to diffuse it as a solution for most projects, since it is currently used only on special occasions where lap splice cannot be applied.

Therefore, the authors strictly recommend the development of more accurate and academic research focused exclusively on the behaviour of couplers, in addition to promoting a complete revision of the ABNT NBR 8548 (1984) standard, which is lagged in terms of instrumentation and parameters of interest to be obtained in the tests, so that the designers have more confidence in specifying this important solution in infrastructure projects in Brazil.

As a final mention, the structure passed with praise in its biggest test, which was the Olympic Games Rio 2016, where under all conditions, public and climatic, as there were incidences of high winds during the event, it can be said that the entire structure behaved within the best conditions of operation, comfort and safety, noting the quality of the designed solution and the entire process for its viability.

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