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CHARACTERIZATION OF THE SEISMIC BEHAVIOR OF A COLUMN-FOUNDATION CONNECTION FOR ACCELERATED BRIDGE CONSTRUCTION

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Abstract

Connections between prefabricated elements are crucial to ensure adequate behavior of structures, especially if these are located on intermediate or high seismic hazard regions and the structural system redundancy is low, as is the case of bridges and wharfs. Due to this reason, prefabrication is usual on bridge elements that will behave within the linear elastic range of response. However, some research in the last decade aims to extend prefabrication to energy dissipating elements such as bridge columns. These developments are highly influenced by the construction practice of each region, making them difficult to adapt in places other than those where they were conceived.

This paper presents the development of a prefabricated emulative energy dissipating column-to-foundation connection. To begin, a conceptual comparative evaluation of the main types of ductile connections use worldwide is presented. According to this review, it was possible to identify that the Grouted Duct Connection has a great potential to be improved for worldwide applications and it has a particular suitability for implementation in Latin American countries. This connection requires the main longitudinal reinforcement of the columns to be projected to fit inside ducts embedded in the foundation that are then filled with no-shrink grout. A successful application of this connection has to provide enough construction tolerances for the elements to fit. Therefore, large diameter bars (No. 14 to No. 18) are currently preferred as longitudinal column reinforcement. Nonetheless, large diameter bars need equally large straight anchorage length that often controls the size of the foundation, making it hard to build, handle and transport. Moreover, reinforcing bars with diameters greater than No. 10 are not available in some regions of the globe such as a few Latin American countries. Due to these problems, this investigation develops a new alternative for column to foundation connection that use galvanized steel ducts to hold bundled bars instead of individual bars, ensuring feasible construction tolerance as well as reducing size and weight of the foundation.

To assess the behavior of the proposed connections, a series of monotonic pullout tests were conducted on single-, two- and three- No. 8 bar bundles for different embedded lengths. These tests allowed proving that for the typical foundation dimensions, the proposed procedure adequately developed bundled reinforcement.

Keywords: Accelerated Bridge Construction, Bundled bars, prefabricated bridge columns, grouted duct connections.

1. Introduction

The permanent development of cities and transportation infrastructure around the world brings with it the execution of several bridge related projects such as new construction, bridge rehabilitation and bridge widening. In general, all of those projects considered traditional construction technics that take months and sometimes years to finish, with the consequent impact on traffic and environment. The use of prefabricated elements for bridge construction has the potential to reduce on-site construction time from month to weeks. This is possible by taking most of the work to a prefabrication plant, which usually have higher material quality, durability, and minimal environmental impact compared to on-site construction [1].

In recent years, Prefabricated Bridge Elements (PBEs) have been used due to their capability to reduce on-site construction time especially on high-congested areas. There are reports of PBEs projects in USA, Japan, Germany, United Kingdom, Spain, France, Taiwan, México, among others [2]. These projects seek to prefabricate the entire structure in order to minimize on-site impact as much as possible; however, there is a great doubt related to the cyclic behavior of PBEs connections [1], this explains the lower applications of PBEs in high and intermediate seismic hazard regions compared to low seismic regions.

Research on this matter have classified PBE connections in two types: energy dissipation connections (EDC) and capacity protected connections (CPC). EDC are the ones close to high flexural demand regions and are responsible for a good plastic behavior of the intended plastic hinge. On the other hand, CPC must remain undamaged during the entire service life of the structure [3]. The column-to-foundation connection falls in the first category. Another common classification of PBE connections refers to the similarity of behavior compared to a traditional cast-in-place concrete solution. According to this, connections can be emulative or non-emulative. The former refers to precast structures with equivalent behavior of a similar cast-in-place structure, while the latter, implies some sort of different behavior [3]. Emulative connections have the advantage of allowing an equivalent comparison with traditional bridge construction technics. Emulative EDC are often made of three different types: Bar couplers, socket connections, grouted ducts, and pocket connections [3].

This paper presents the development of an emulative prefabricated energy dissipation connection between column and foundation based on the state of the art in this matter. To begin, a conceptual comparative evaluation of the main types of ductile connections use worldwide is presented. According to this review, it was possible to identify that the grouted duct connection has a great potential to be improved for worldwide applications and it has a particular suitability for implementation in Latin American countries. A successful application of this connection has to provide enough construction tolerances for the elements to fit. Therefore, large diameter bars (No. 14 to No. 18) are currently preferred as longitudinal column reinforcement. Nonetheless, large diameter bars need equally large straight anchorage length that often controls the size of the foundation, making it hard to build, handle and transport. Moreover, rebars with diameter greater than No. 10 are not available in some regions of the globe such as in some Latin American countries. Due to these problems, this investigation develops a new alternative for column to foundation connection that use galvanized steel ducts to hold bundled bars instead of individual bars, ensuring feasible construction tolerance as well as reducing size and weight of the foundation.

2. Connection types for precast concrete elements in seismic regions

2.1 Bar couplers connection

Bar couplers are special devices used to join separate bars. These elements transfer axial loads from one bar to the other ensuring reinforcement continuity and eliminating lap splices (Fig. 1a). The joining method varies with each coupler manufacturer. The main advantage of bar couplers connections is the possibility of placing the connection anywhere along the column, even in the plastic hinge region. Nevertheless, doubts remain about the seismic behavior of this connection and the consequent lack of design recommendations. Recent research addresses this problem and aim to increase current understanding of bar coupler connections on high demanded regions [4].

On the other hand, an important disadvantage of this connection is the market availability of properly tested and verified bar couplers. This issue limits the application of this connection to specific regions. Furthermore, construction tolerances are very small on this system; hence, every project needs highly train and specialized workers that may be unavailable or unaffortable.

2.2 Grouted duct connection

For this type of connection, straight reinforcement bars projecting from one element are grouted in corrugated ducts embedded in the other (Fig. 1b). The grouted duct connection has a particular interest because it requires minimum amount of connecting material and allows few changes in element design and detailing [3]. Nonetheless, construction tolerances are usually small and depend on the duct-to-bar diameter ratio and the number of bars connected in a given section; thus, construction process can be simplified and enhance if few bars of large diameter are used. The ducts can be in the column or the foundation. The second option is preferred because implies minimum changes in the plastic hinge region.

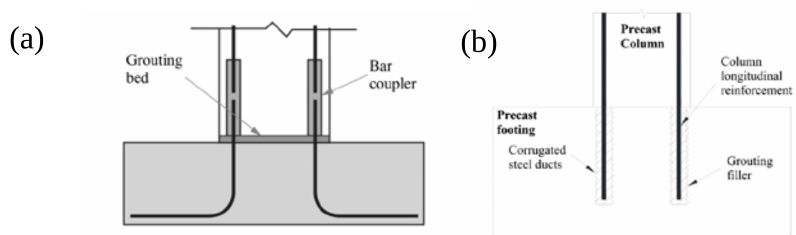

Fig. 1 – (a) Bar coupler connection [3]. (b) Grouted duct connection [5]

2.3 Pocket connection

This connection is similar to the grouted duct connection, but in this case, a big “pocket” receives all the longitudinal reinforcement instead of a single duct per longitudinal bar. Connection process begins with placing of the column and leveling, and ends with grout pouring in the remaining space (Fig. 2a) [3]. Non-shrink grout is preferred because it has small volume variations.

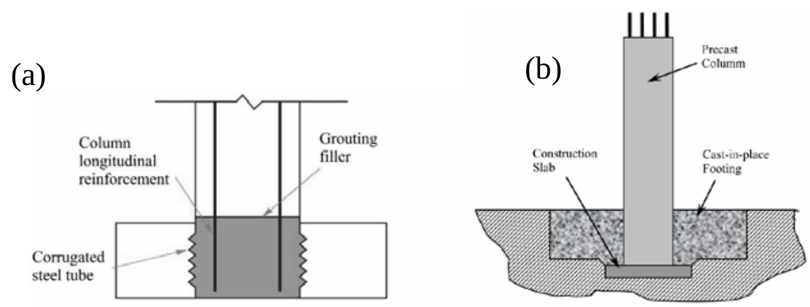

Fig. 2 – (a) Pocket connection [3]. (b) Socket connection [6].

Foundation’s longitudinal reinforcement can pass through the pocket or be concentrated on the adjacent area at each side of the pocket. The former option affects column installation prior grouting and the latter generates reinforcement congestion inside the foundation and around the pocket. Joint design and detailing are key aspects of this connection. The main advantage offered by pocket connections are the large construction tolerance provided inside the pocket. However, the amount of connecting material is usually large and foundation’s reinforcement detailing complex.

2.4 Socket connection

On this method, the foundation receives the column without any kind of reinforcement interlock between elements [3]. The precast columns have a rough surface in the connected region to increase bond resistance. Socket connections can be made in two different ways: 1) The column is prefabricated and the foundation is cast-in-place around it after column leveling and bracing (Fig. 2b) [6], and 2) both, column and foundation, are precast; in this case the foundation element has a central hole that receives the column and it is seal with grout

[7]. The fact that there is not crossing reinforcement between elements simplifies transportation and handing of precast elements. However, this connection presents the same disadvantage pointed out for the pocket connection in terms of foundation reinforcement complexity.

3. Proposed column-to-foundation connection for Latin America

This section presents a review of the connections presented previously according to the following criteria: construction features (tolerances and equipment needed for field installation), time spend on field installation, element-detailing complexity from a precast solution compared to an equivalent cast-in-place solution, and connection performance.

Construction features: According to the construction equipment available in Latin America, the bar coupler connection has the greatest disadvantage of the four connections considered, because high quality bar couplers are hard to find in Latin American markets; furthermore, construction tolerances provided by this method are very small (millimeter only); hence highly skilled workers are needed. In contrast, the grouted duct connection is very flexible in terms of construction tolerances and installation equipment. The reason is that the number of connections in a given section and the duct-to-bar diameter ratio are design variables that can be optimized to avoid grout pumping equipment and provide feasible tolerances. On the other hand, the socket and pocket connections provide the maximum construction tolerances of the four connections considered; however, the latter needs a considerable amount of grouting that increase its cost.

Time spend on field installation: All of the evaluated connections spend approximately the same time on field installation, except the socket connection with cast-in-place foundation.

Element-detailing complexity from a precast solution compared to an equivalent cast-in-place solution: The greater the similarity with current practice, the easier its implementation. Therefore, this factor is very important for a quick and easy adoption. According to this, bar couplers connection requires a special detailing at the bottom of the column that introduces substantial differences with conventional cast-in-place columns; although, foundation remains equal to a traditional one. The opposite happens in socket and pocket connections. For these cases, columns have the same design and detailing that cast-in-place construction, but foundations required special reinforcement arrangement due to interferences with the column reinforcement. Moreover, socket connections with precast foundations required particular design methodologies to address force transfer mechanism and local connection behavior [7]. On the other hand, properly designed grouted duct connections have columns and foundations essentially equal to an equivalent cast-in-place solution. This is possible if ducts arrangement generates minimum interference with foundation reinforcement.

Connection performance: For this factor, the presence of any abnormal device in the plastic hinge region is undesirable. In general, all the considered connections maintain the plastic hinge region untouched, except for the bar couplers connection. In this case, couplers are precisely in the plastic hinge region; thus, a different nonlinear performance compared to a cast-in-place solution can be expected.

According to the criteria and analysis presented herein, the grouted duct connection has a great potential for implementation in Latin America as long as allows feasable construction tolerances, avoid grout-pumping equipment, and minimized interference with foundation reinforcement. According to Brenes et al. [8] and Steuck et al. [9], a good option is the use of large diameter bars (No. 11 to No. 18); nonetheless, large diameter bars required long development lengths that usually control the depth of the connecting element, such as foundations and girders [10, 11]. Moreover, No. 11 bars or greater are not available in several countries around the world, and have limited applicability in ductile elements [12, 13]. Therefore, the use of bundle smaller diameter bars (No. 6, 7 and 8) offers a new alternative to extend the application of grouted duct connections for PCEs.

4. Prototype bridge

The study of this connection was approached on this research by defining a prototype bridge, representative of the bridge engineering practice in Colombia. The prototype bridge characteristics were selected based on the Colombian and Bogotá’s bridge inventory.

The prototype is a two 25m span bridge over pass of an urban intersection. A lateral view of the bridge is shown in Fig. 3. Superstructure is a typical slab-beam deck with prestressed isostatic-beams and reinforced concrete slab suitable for precasting. The bridge is 20m wide, enough for four 3.65m lanes, four 0.50m berms, two 0.30m railings, a central 0.60m fence, and a 2.20m pedestrian platform. The approach embankments are made of reinforced soil, so abutments and pier are concrete moment resistant frames.

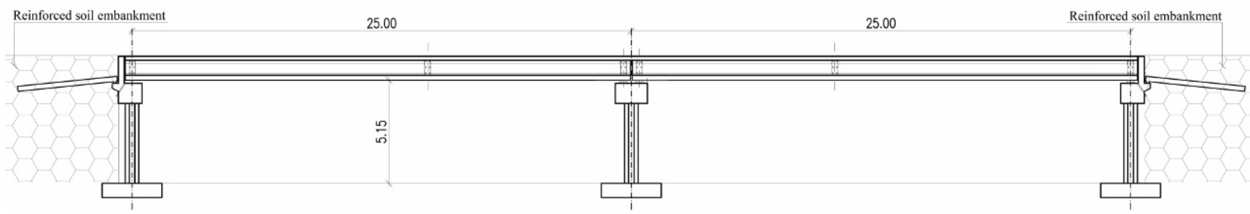

Fig. 3 – Lateral view of prototype bridge

Substructure was proposed in 28MPa compressive strength reinforced concrete. Each frame has four 0.28m-side octagonal columns of 4.00m high fixed at the based in a pile cap foundation and at the top in a 1.0m high per 1.60m wide bent cap as shown in Fig. 4. Column high was defined to ensure the minimum 5.00m clearance required in urban over pass structures. In addition, column section dimensions were selected for a 0.20 axial load index under the service limit state. This substructure type can be built with PBEs with separate elements for columns, foundation and bent cap. Further details on the prototype bridge can be found in [14].

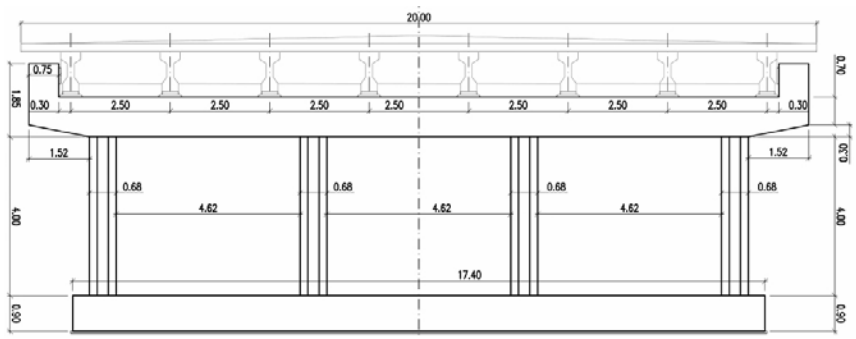

Fig. 4 – Substructure moment resistant frame

4.1 Grouted duct connection details for the prototype bridge

Fig. 5 shows a 3D scheme and a section of the proposed connection. The ducts are 100 mm nominal diameter corrugated-galvanized steel duct, with 0.3 mm thickness and 3.0 mm high deformations in a spiral arrangement of 25 mm pitch. This type of duct is common of posttensioning applications. Column longitudinal reinforcement consist of 3No.8 bar bundles, each of whom fits inside one duct. Each duct pair has a 400mm-hose responsible for taking out all air inside the duct during grouting placement prior column leveling. Minimum grout strength was set on 32MPa. At the column-to-foundation interface, a 50mm-grout bed is proposed according to Restrepo et al. [15] recommendations.

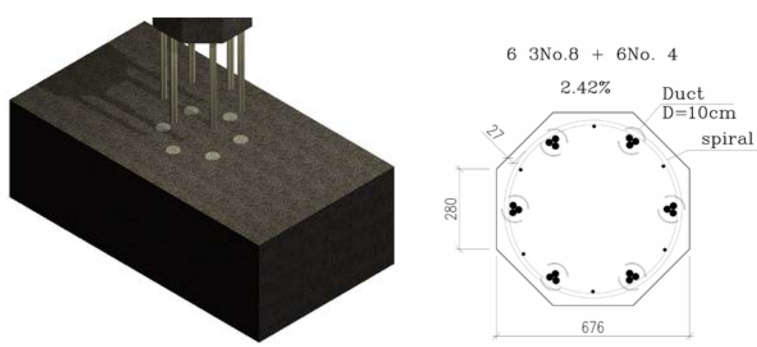

Fig. 5 – Connection process and column cross-section

Column reinforcement was selected based on AASHTO LRFD [11] Specification for cast-in-place reinforced concrete elements with spiral confinement. Seismic design of the bridge for a high seismic hazard region in Colombia led to a longitudinal reinforcement ratio of 2.42%, achieved with six bundles of 3No. 8 as shown in Fig. 5. Additional 6 No. 4 bars were located between bundles to fulfil confinement requirements in the plastic hinge region. These bars are not connected to the foundation. Some researchers have stated concern about non-connected reinforcement on grouted duct connections, because plastic deformation can concentrate in one crack, and severe tensile stresses could be demanded on connected reinforcement [16]. However, this damage concentration is unlikely to occure when non-connected reinforcement represents a small amount of the total longitudinal steel ratio. For the prototype bridge, non-connected bars represent only 9.6% of the total reinforcement ratio; thus, damage concentration at the connection interface is not expected.

5. Bundle bars development length grouted in ducts

Details defined in the previous section are missing one important value: development length. This measure usually controls the depth of the foundation and is responsible for adequate force transfer and appropriate hysteretical behavior. This section explores current code provisions for bundle bars development length, revises available information about reinforcement grouted in ducts and apply these provisions to the column-to-foundation connection of the prototype bridge.

5.1 Bundle bar code recommendations

The use of bundled bars in conventional reinforced concrete elements has been considered in most design and construction specifications around the world. However, there is no agreement between design codes about the development length that should be used for bundled bars [10, 11, 12, 13, 17].

ACI 318-14 [10] and AASHTO LRFD [11] recommend a development length equal to that of an individual bar for two-bar bundles. Nonetheless, for three- and four-bar bundles the development length of the individual bar must be multiplied by increment factors of 1.20 and 1.33, respectively. This consideration is based on the study of Jirsa et al. [18]. As shown in Fig. 6a for three bar bundles, the increment factors are calculated by dividing the total perimeter of the bars by the contact perimeter of the bundle. This approach will be referred in this paper as the maximum perimeter assumption.

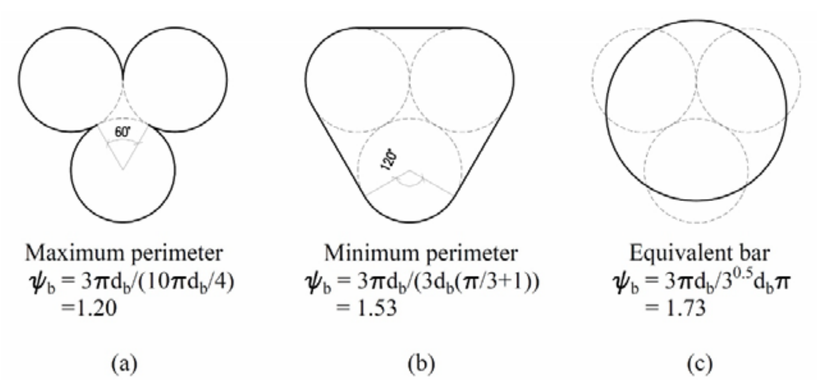

Fig. 6 – Alternative assumptions for bundles used in development length calculations

On the other hand, AASHTO SGS [12] and CALTRANS [13] allow the use only of two and three-bar bundles for ductile concrete elements and require an increment factor of the individual bar development length of 1.20 for two-bar bundles and 1.50 for three-bar bundles. This increment factors are calculated by dividing the total perimeter of the bars by the length of the contact perimeter shown in Fig. 6b. This approach will be referred in this paper as the minimum perimeter assumption.

In Europe, the *fib* Model Code [17] states that the development length of bundled reinforcement should be calculated using the diameter of an equivalent bar with the same cross-sectional area of the bundle (Fig. 6c). This approach is commonly known as the equivalent bar assumption.

Comparing the three approaches presented and their factors shown in Fig. 6, it may be observed that they agree in terms of an increased development length for bundled bars over a single bar. However, the amount of this increment is significantly different between each approach. In general, the maximum perimeter assumption yields the shortest development lengths, while the equivalent bar assumption results in the greatest. For instance, if the equivalent bar assumption is considered for a three-bar bundle, the resulting development length is 44% longer that the corresponding length for the maximum perimeter assumption under the same conditions. This considerable difference highlights the importance of defining the most appropriate contact perimeter assumption in order to avoid excessive development lengths, which in turn create unnecessary difficulties while dimensioning and detailing a structure with bundled reinforcement.

5.2 Bars grouted in ducts

Bond behavior and performance of grouted duct connections has been investigated in previous studies [8, 19, 20]. All of them recognized the suitability of the connection for seismic regions and recommended development length expressions for a single bar per duct. In addition, Steuck et al. [9] studied bond behavior of large diameter bars (No. 10 to No. 18) grouted in 203mm rigid steel ducts based on 14 monotonic pullout tests. They concluded that—for conditions similar to those tested—large bars grouted in ducts could achieve yielding and fracture strengths with embedment lengths of 6 and 10 bar diameters, respectively. Extending Steuck et al. [9] research, Pang et al. [21] performed tests of three full-scale beam-to-column connections with large diameter bars. From this study, they found that this connection has emulative performance and could be used in regions of high seismicity.

Recently, Tazarv and Saiidi [22] performed three pullout tests of two No. 8 bar bundles anchored in corrugated steel ducts filled with ultra-high-performance-concrete (UHPC). From these tests, they observed that the effect of bar bundling was negligible. However, the use of UHPC as filling material influences the results; hence, this conclusion cannot be extended to grouted-filled duct connections. To summarize, to the best knowledge of the authors, there is no available information related to the performance of bundled bars anchored in corrugated steel ducts filled with grout.

5.2 Development length for prototype bridge connection

Steel reinforcement subjected to tension and anchored directly in concrete have two general failure modes: 1) splitting failure, and 2) pullout failure. Splitting failure takes place when radial cracks around reinforcement reach the element´s surface or an adjacent bar crack; in that moment, a splitting crack forms along the anchored bar and concrete moves away from the bar. As a result, all force transfer is lost. If concrete cover, bar spacing or transverse reinforcement is sufficient to delay the splitting crack formation, the anchor bar reaches its maximum capacity and failure will be controlled by shearing along a surface at the top of bar lugs. This is called a pullout failure [23].

For design purposes, development length expressions for single bars in tension anchored directly in concrete have been recommended [10, 11, 12, 13, 17]. In general, these equations are drawn from regressions of extensive test data. Special care has been taken in order to address reasonably well the splitting strength rather than the pullout strength since the former is usually the lowest [23]. The variables considered for most of these expressions are: concrete compressive strength (f'_c), reinforcement yielding strength (f_y), epoxy coating, deformed or plain bars, concrete cover (*C1*), bar spacing (*C2*), confinement in form of transverse reinforcement, casting position, and presense of hooks or heads at the end of the anchor bar. In seismic regions, some specifications require longer development lengths to ensure $1.25f_y$ [11].

For the prototype bridge considered in this paper, the column longitudinal reinforcement development length was calculated for a cast-in-place solution. In this case the variables have the following values: straight deformed bars without epoxy coating casted vertical, f'_c = 28 MPa, f_y = 420 MPa, *C1* = 1200mm, *C2* = 275mm, and a No. 5-bar spiral with a 200mm pitch as transverse reinforcement. Fig. 7a shows development length results for various bar sizes according to five international codes. As can be observed, No. 8 bars require between 610mm and 710mm, while No. 10 bars require between 780mm to 1170mm. These lengths include the seismic increase factor mentioned before when applicable.

For the grouted duct connection solution, development length expression for single straight deformed bars have been proposed by Matsumoto et al. [19], Brenes et al. [8], Steuck et al. [9], and the PCI [24]. Fig. 7b shows development length results according to these expressions based on a grout compressive strength of 32 MPa. Results evidence similar length values compared to the cast-in-place solution for the prototype bridge. For instance, No. 8 bars require between 600mm and 720mm, while No. 10 bars require between 710mm to 1100mm. This similarity of results between cast-in-place and grouted duct connections and the scatter found in both cases can be explained by the fact that, at the column-to-foundation connection, failure is dominated by pullout rather than splitting.

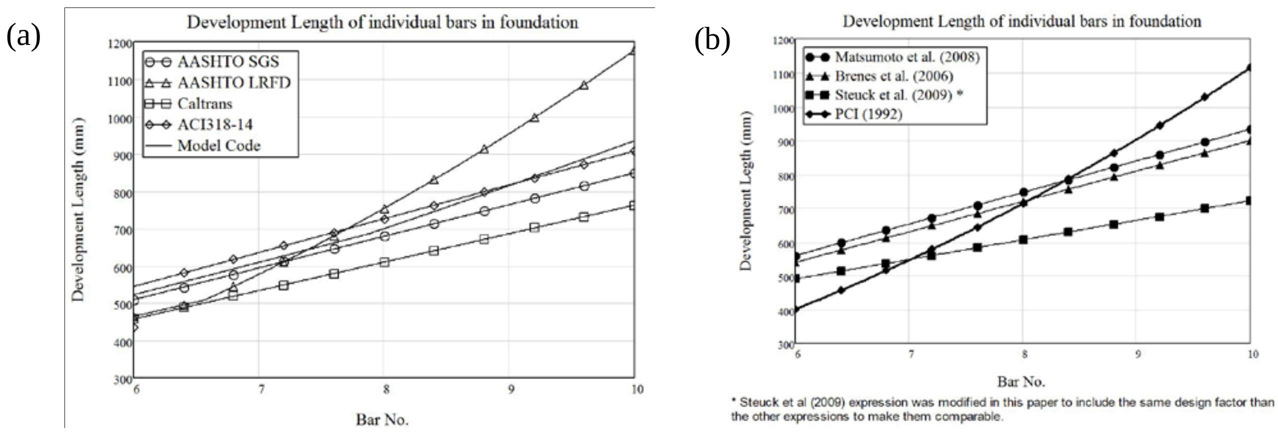

Fig. 7 – (a) Development lengths for single bars in a cast-in-place connection. (b) Development lengths for single bars in a grouted duct connection.

Adding the corresponding bundling factor presented in section 5.1, 3No.8 bundles requiered a development length between 850mm according to ACI318-14 [10] and 1430mm according to the Model Code [22] for a cast-in-place connection. The same analysis cannot be done for the grouted duct connection, due to the lack of design recommendations for bundled bars anchored with this procedure.

The considerable scatter found for conventional concrete applications and the lack of information about bundled bars grouted in ducts, evidenced the need to conduct an experimental study that helps to fill this knowledge gap. Only representative results of a larger experimental program are presented in the following sections. Further details can be found in [25].

6. Test setup

Test specimens were solid concrete blocks with the same height and width of 900mm and variable depth of 550 mm, 850 mm and 1000 mm, suitable for testing embedded lengths up to 900 mm. In the center of the squared side a galvanized steel duct, typical of post-tensioning applications, was embedded. The clear distance between the duct and the edges of the block was set on 400 mm in order to provide enough confinement to the anchor bars. This resulted in the prevention of splitting failure. This study used the same duct described in section 4 for the prototype bridge. The concrete block reinforcement was designed to remain elastic under the maximum expected load to prevent block failure.

Non-shrink grout was used as connecting material similar to previous studies [8, 9, 17, 18]. The water-to-grout weight ratio used in each test was 0.14 for semi-fluid consistency according the manufacturer's instructions. Samples of reinforcement bars, concrete and grout were tested. The average yielding and ultimate strength of the steel samples were 467 MPa and 696 MPa, respectively. Concrete and grout (f'_c and f_{cg}) strengths were measured on the day of testing. Grout strengths fell between 32.0 MPa and 36.0 MPa, while concrete strengths were between 58.0 MPa y 62.0 MPa. It is important to notice the high strength obtained for concrete, which is justified by the high quality control and rigorous curing process done at the plant.

The test setup is shown in Fig. 8. This setup was designed in such a way that it can be used for any number of bars per bundle without further changes. Tested bars are anchored symmetrically at each side, implying a double pull-out test for each specimen. The connecting process was performed in five-steps described as follows: 1) cut the tested bars to a proper length; 2) align each block in front of the other; 3) suspend the bars within the ducts; 4) close each side of the duct; and 5) pour grout through the injection holes at each block. Load was applied symmetrically by two hydraulic rams placed at a 10.6 in. [270 mm] clear distance from the edge of the loading plate of the ram to the outer edge of the duct. This distribution of load and clear distance were defined to avoid introducing compression stresses in the bonded region, where concrete, grout, and steel bars must be subjected to bond transfer stresses only [9, 23]. The presence of rolling tubes under each block ensures that the whole force applied by the rams is transferred to the tested bars.

Displacement of each block was recorded with two linear variable displacement transducers (LVDT), both placed in the unloaded face in contact with regular concrete (Fig. 8).

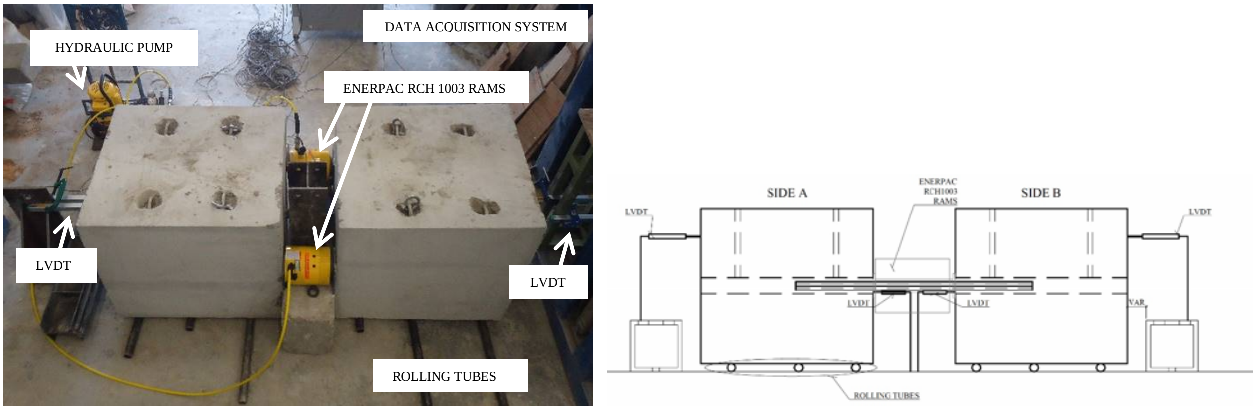

Fig. 8 – Test setup.

Monotonic tests were force-controlled starting at a load of 29 kN in each ram, which increased in slow load increments of 9.8 kN applied with a hand-operated hydraulic pump. All tests were carried out until load dropped below 20% of the maximum registered value, considering this the failure point. Loading rate was controlled to limit reinforcement stress increments to values smaller than 690 MPa/min, ensuring that the test would remain under the maximum recommended rate of loading used for conventional steel tensile test. Monotonic tests were conducted at this stage of research, since monotonic loading has been found to present the same failure modes than low-cycle loading typical of earthquake demands [26]. Moreover, monotonic test results have been proved to be an approximate envelope curve of cyclic test [27].

7. Test results and discussion

Tensile stress-displacement responses of 3No.8 bar bundle tests with embedded lengths of 150mm, 350mm, 450mm, 750mm and 900mm are presented in Fig. 9. Results for single and two No. 8 bars with 150mm embedded length are also presented. The displacement response plotted is the relative displacement between the two blocks, calculated as the sum of the measurements of LVDTs placed in the unloaded face of each block. This measurement was selected because is a direct estimate of the total movement of the two connections that act simultaneously in each test. The average bar tensile stress is calculated based on the nominal bar area. Fig. 9 shows that the yielding stress of the three-bar bundles was exceeded with embedded lengths as short as 350mm, reaching stresses near fracture.

The 900mm embedded length was selected based on recommendations of AASHTO LRFD [11] for conventional normal weight reinforced concrete considering the appropriate modification factors for bundling (factor of 1.20 according to Fig. 6), uncoated bars, vertical casting position, clear cover greater than 75mm, and good confinement (see Fig. 7a for No. 8 single bar development length). Results presented herein shows that the proposed connection reached fracture of reinforcement for embedded lengths near 2/5 than the calculated value according to AASHTO LRFD [11]. This is believed to be explained by the confinement provided by the duct and the safety factors included in the design equations that account for dynamic loading, materials uncertainties, and quality construction.

Surface crack patterns were identified at different load levels for each test. In general, surface cracks were first observed on grout at a radial pattern spreading outwards from the bar to the duct. This behavior was evident in the first stage of all tests. As the load increase, radial cracks extended to the surrounding concrete depending on the magnitude of the total tensile force developed at the connection combined with the clear distance between bars and duct.

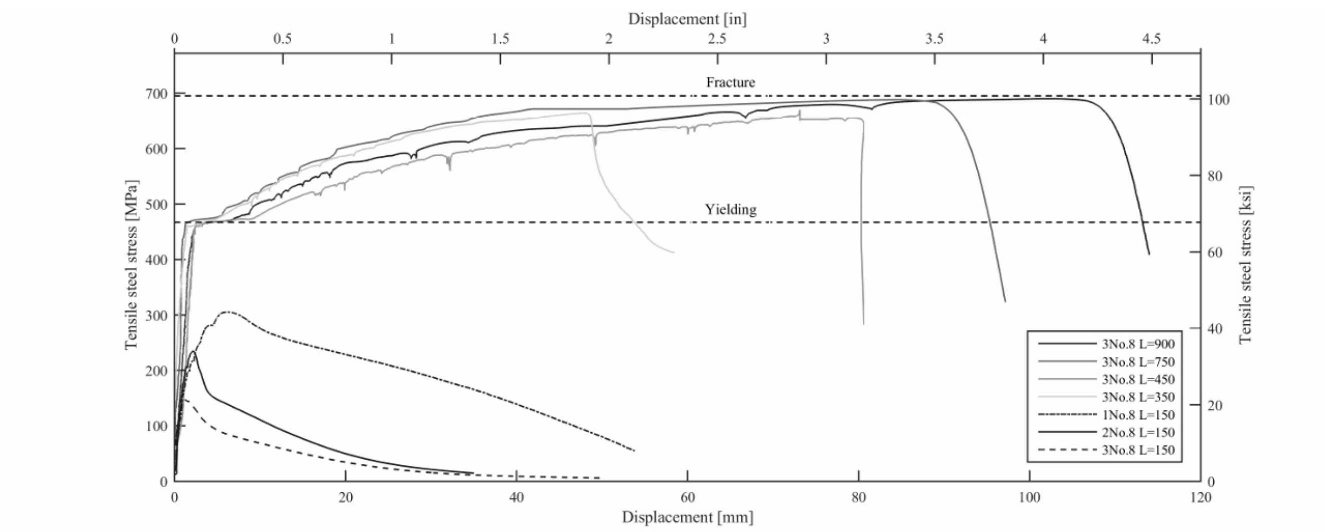

Fig. 9 – Tensile stress-displacement responses of bundle bar tests

After each test, anchor bars were pulled out completely to understand the failure mode. All tests evidenced a general pullout failure; however, three specific failure modes could be identified. A description of each one is presented as follows:

Mode 1: Failure took place at the grout-to-bar surface with shearing of a grout cylinder of the same diameter of bar lugs. Concrete and duct remain essentially undamaged. This mode was observed only in the single bar test performed.

Mode 2: Failure started at the duct-to-surrounding concrete surface and extended along it until a point where grout fractures in an approximate 45-degree angle. At this point, the duct unfolded and failure surface passed to the grout-to-bar interface similar to mode 1. Damage in the surrounding concrete was occasionally observed. This was the failure mode of tests with two- and three- No. 8 bar bundles and embedded length shorter than 450mm.

Mode 3: Failure was dominated by fracture of the anchor bars. Nonetheless, surface damage was similar to mode 2. This type of failure was typical of tests with large embedded lengths (750mm and 900mm) that were long enough to transfer the fracture load of the bundle bars in spite of the formation of the failure cone at which bond transfer was lost.

In order to identify the effect of bar bundling, three test were performed on specimens with one, two and three bars per bundle for the same embedded length of 150mm. Stress-displacement responses from these tests are shown in Fig. 9. The peak bar stress in tests with three and two bars were 50% and 75% of the value reached for the single bar test, respectively. Hence, the relation between the bar peak tensile stress and the number of bars seems to not be entirely represented by the increment factors used in design to account for bundling. Nevertheless, this is only one set of experiments, so further research (including cyclic and dynamic tests) is under development to expand this conclusion. It is important to note that none of the 150mm tests reached yielding; therefore, the different connection performance observed among these tests is believe to be related to the effect of the number of bars only.

8. Conclusions

This paper presents the development of a prefabricated emulative energy dissipating column-to-foundation connection suitable for application in Latin America and worldwide. To begin, a conceptual comparative evaluation of the main types of ductile connections use worldwide was made. According to this review, it was possible to identify that the grouted duct connection has a great potential to be improved if large diameter reinforcing bars are replaced by bar bundles of smaller bars that provide the same steel area. This ensures feasible construction tolerance as well as reduces foundation size and weight.

The six monotonic pullout tests conducted on No. 8 bar bundles for different anchorage lengths allowed to prove that bar bundles are adequately developed with the proposed procedure. This tests evidenced that 3-No.8 bar bundles could achieve stresses near fracture with embedded lengths as short as 350mm; thereforce, small development leghts with this connection can be expected; however, there are not design recommendations for bundled bars grouted in ducts.

The effect of the number of bars per bundle does not seems to be entirely represented by the increment factor currently used in design practice to account for bundling. Therefore, a conclusion about the appropriate alternative assumptions for development length calculations of bundle bars (Fig. 6) cannot be drawn yet. However, detailed evaluation of these assumptions can be found in [25] based on further test data.

This research still on going with the execution of cyclic pullout tests to validate the proposed connection and propose a development length equaton suitable for design. After these tests, full-scale column-to-foundation connection cyclic and shake table tests are scheduled to assess element behavior prior field applications.

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10. Copyrights

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