Abstract

In the current practice, at the end of life of a reinforced concrete structure, it is destructively demolished and the demolition waste is landfilled or recycled. This approach is clearly wasteful of energy, creating serious environmental pollution and at high cost. However, design for demountability/deconstruction (DfD) of reinforced concrete structures would facilitate the future reuse of structural elements at the end of their life, potentially achieving a significant reduction in embodied energy of structures as well as giving the clients the benefit of retaining the value of their assets.

In this paper, recent research developments and practical applications of DfD of reinforced concrete structures are reviewed and key technical issues are discussed. The main focus was on connections that should be designed in such a way to allow demounting. The main achievements are outlined, for each type of dry and semi dry connections, along with the aspects that still need to be developed. It is concluded that only semi-dry connections are currently implemented but information available in the literature on dry connections between structural elements is still very scarce. The paper concludes with an outline of some future opportunities and challenges in the application of DfD in concrete construction.
Keywords: Demountable structures; Dry connections; Reinforced concrete; State-of-the-art.

1. INTRODUCTION

The construction sector remains nowadays as one of the main contributors to the worldwide carbon and heavy metal gas emissions, and consequently greenhouse gas pollution [1]. The emissions are mainly caused by the extraction and production of materials, especially Portland cement, accounting for 5 to 8% of total human-driven CO$_2$ emissions [2, 3] (i.e. 1000 to 1200 kg of CO$_2$ are emitted due to the fabrication of every 1000 kg of Portland cement [4]). There is also a very significant environmental impact related to the construction waste storage and treatment in landfills. An impact reflected in air pollution (due to the dust released [5]), water contamination (due to natural radioactive and toxic elements present [6]) and a detrimental effect on the local ecosystems [7]. Construction waste represents about half of overall landfill volumes [8] of which cement-based materials like concrete represent about one quarter [9].

The substantial impact of the construction sector in public health and ecology represents a major challenge, so new solutions can be developed towards "green construction" [10]. In terms of structural engineering, the current challenges mainly rely on two themes: 1 – the incorporation of waste products in materials, so a full recycled production can be achieved [11]; and 2 – the conception of structural configurations in which the structural elements (beams, slabs, columns and foundations) can be disassembled and reused in new structures [12]. The accomplishment of these objectives would dramatically reduce the amount of natural (raw) resources extracted, the need to produce new materials and the accumulation of waste in landfills [13].

Traditionally, steel is the material more suitable to fulfil the demand for more sustainable construction with less ecological impact. However, the use of structural steel frequently turns
out to be less economical, due its more complex production requiring intensive energy and less availability compared to concrete [14]. Consequently, research has started to be carried out more intensively in the last decade on topics such as concrete recycling [15-17] and concrete structural design for deconstruction and material reuse [18-20]. Along research, common practice in structural engineering already applies recycled raw materials in concrete production [21] and semi-dry connections between reinforced concrete structural elements [22]. These advances are not only motivated by an increased environmental awareness in society, which tends to be reflected in legislation and public funding, but also by the speed and economic benefits (value of the assets is retained for longer time) compared to new construction [23].

The question of how best to join the many parts of a structure is probably as old as building construction itself. Clearly, the principal role of any structural connection is to transfer forces safely between various components meeting at that joint. Therefore in the design of connections a clear understanding of load paths, i.e. the mechanism by which various components of the joint itself transfer loads through the connection, is essential. On the other hand, connections in DfD need also to be designed in such a way to allow demounting of structural elements undamaged, permitting their reuse in other structures.

In semi-dry connections, small portions of cast-in-place concrete are used to connect precast elements. Therefore, conditions for structural disassembly and reutilization are more favourable compared to pure wet connections, in which reutilization is not possible. Although semi-dry connections represent a step forward towards sustainability in construction, the path clearly leads to the achievement and implementation of totally dry connections [22]. In dry connections, the precast structural elements are directly connected to each other and no cast-in-place concrete is used. Consequently, reutilization can be easily carried out at the end of the structure’s life, without a need for wasting or even recycling, potentially achieving more than 50% reduction in embodied energy of structures.
Few investigations have focused on demountable composite steel-concrete constructions using various types of bolted shear studs, rather than welded, allowing the reuse of the steel beams. However, this technique would not currently permit the reuse of concrete slabs that are generally demolished. Various bolts, including friction-grip bolts [24], threaded bolts tightened by exterior nuts [25] and exterior nut-tightened threaded bolts with single embedded nuts [26], have been studied with different degrees of success in achieving the shear transfer forces between the concrete slab and steel beams. However, the demountable shear connectors are rarely used in composite construction in practice due to the lack of detailed design rules concerning their behaviour. These demountable steel concrete composite connections are not covered in this paper.

This paper presents a state-of-the-art review on dry connections between precast reinforced concrete elements. The current engineering practice is assessed at first, and then a description and discussion of each solution proposed in the literature for this type of connection is presented. The main research trends are outlined, and further developments are proposed towards sustainable reinforced concrete (RC) construction.

2. CURRENT PRACTICE IN STRUCTURAL ENGINEERING

Currently, at the end of life of a structure, although all the steel and concrete materials remain serviceable, the structure is demolished destructively, large steel elements are recycled by energy-intensive melting [27], and the rest of materials are rather landfilled or recycled. This approach is clearly wasteful of energy, creating serious emissions and potentially costly. To drastically reduce such waste as well as reducing the embodied energy of structures, it should become the norm that structures be designed and constructed for reuse after service. However, that goal is still to be achieved in the case of RC structures, that generally dominate the construction market worldwide [14]. The lack of knowledge on the structural behaviour of
easily demountable (dry) connections between RC elements [22], including safety and structural strength, is still limiting its practical application.

Therefore, current practice of demountable structures relies mainly on reinforced precast concrete structures with semi-dry connections between structural elements. Deconstruction of RC structures with semi-dry connections, although feasible, is not an easy procedure. Parts of cast-in-place concrete or injected grout need to be mechanically destroyed and removed as well as cutting of steel reinforcement. Then, reconstruction follows the inverse path: parts of cast-in-place concrete need to be added and some reinforcing bars welded. Since the application of these semi-dry connections in new Civil engineering constructions is still not distant in time [22], most of the structures containing semi-dry concrete connections are still within their service life cycle. However, deconstruction/reconstruction has not been practiced so far. Nowadays, there are mainly two types of semi-dry connections in RC structures: 1 – dowel shear connections; and 2 – moment-resisting connections with continuity bars.

2.1 Dowel shear connections

Dowel shear connections are the most commonly used semi-dry connection between precast RC elements [28]. Thus, recent research carried out on concrete semi-dry connections does not usually address dowel shear connections. In this type of connections, typically, the precast concrete elements contain pre-drilled holes that are crossed by a bolt. The connection is filled and established when grout is injected in the remaining clearance in the holes. Another way to establish a dowel connection is depicted in Fig. 1, from the work of Metelli et al. [29], showing the case of a dowel connection between a column and the foundation of a precast RC structure. As can be seen, continuity reinforcement extends beyond the end of the column and enters the pre-drilled holes in the foundation (Fig. 1(a)). The connection is later established when grout is injected, in order to fill the remaining clearance in the holes and the gap between the column and the foundation as depicted in Fig. 1(b).
2.2 Moment-resisting connections with continuity bars

In beam/beam or beam/column connections, flexural stress needs to be transferred between the structural elements connected. Therefore, in these cases, dowel shear connections are not feasible, and a different moment-resisting connection solution is implemented. The most typical configuration can be seen in Fig. 2, taken from the study published by Xiao et al. [30], where continuity reinforcement extending beyond the top and bottom ends of the elements (beam and column) is welded. The connection is then established when cast-in-place concrete is added in order to cover the top and bottom welded reinforcement. In turn, shear is transferred through a shear key created by the fitting of the beam and column ends.

3. DEMOUNTABLE DRY CONNECTIONS

Research performed on demountable dry connections in RC structures is still scarce and recent. The idea of demountable concrete structures was initially introduced by Reinhardt [31] in 1976 and a few systems were developed in the construction sector. However, their use and application were very limited due to the lack of knowledge and physical testing of such systems. The key to success of reusable structural components is to make the structural system easily demountable at the end of life. Only a few connection solutions were tested, and even fewer were subjected to finite element analysis and parametric studies. Consequently, a more precise understanding of the strength mechanisms involved in this type of connections, their structural behaviour and capacity, is still limited. Due to that fact, there is an absence of safe and optimized design recommendations in the norms, so structural engineers can opt for demountable RC dry connections in their practices.

In this section, the research carried out on RC dry connections is detailed and discussed. Since the design of such connections depends on the elements being connected, the structure of the section is organized and divided in each type of connection studied so far in the literature.
3.1 Beam/column connections

Due to the type of stresses transferred, bending and shear, beam/column connections are normally the most challenging to materialize and problematic type of connections in precast RC structures [32]. In 2016, Aninthaneni et al. [34, 33] proposed three non-prestressed solutions (see Fig. 3) for a dry connection between a beam and a column of a precast RC structure, which incorporates threaded pre-tensioned bolts and a steel end plate. In turn, the beam and column have embedded threaded rods to accommodate the bolts. The main feature of these 3 connections is in the connecting element that is a steel end plate embedded in the beam in Type-1 connection (end plate connection), an angle plate in Type-2 (angle connection) and the steel end angle plate encases the beam in Type-3 (tube connection). The connection types, along with a monolithic connection, were subjected to the same seismic action to assess their behaviour. Furthermore, four types of fill material for the gaps in the beam/column contact zone were examined: natural rubber sheets, grout, a dental plaster and epoxy resin. The use of a fill material in these connections assures that the pretension load applied in the bolts has a more uniform distribution.

The results obtained showed a similar behaviour for Type-1 connection compared to the monolithic connection. The location of the plastic hinge occurred away from the beam end and in front of the steel end plate, showing that the connection segment was stronger than the beam capacity itself. However, Type-2 and Type-3 exhibited less stiffness and strength compared with the control specimen as well as Type-1. Compared to Type-2 and Type-3, Type-1 connection has the beam’s main reinforcement welded to the steel end plate and, consequently, the tensile force in the reinforcement was easily transmitted via the connection.

While the maximum lateral load of Type-1 connection varied between 175 kN and 185 kN, for a lateral drift of approximately 4%, the maximum lateral load of Type-2 connection varied between 110 and 155 kN, for a lateral drift of approximately 2%. In Type-2 connection,
tensile force in the beam’s main reinforcement is transferred to the steel end plate through the
surrounding concrete and the bolts (strut and tie mechanism), which is a more sinuous path
compared to the Type-1 stress transfer, highlighting the causes of strength and ductility
reduction, and the severe cracks observed in the connection area during the tests of Type-2
connection. In turn, Type-3 connection behaviour was similar to Type-2, with strength varying
from 110 kN to 140 kN for a lateral drift of approximately 2%. It was concluded therefore that
the steel plate encasement does not largely influence the connection strength and ductility.
Type-2 and Type-3 connections also revealed a structural behaviour more dependent on the fill
material used. In this context, the rubber sheets and the epoxy resin caused premature slip in
the connection, and thus their application as fill material is not recommended.

Although the results obtained for Type-1 connection were very encouraging, there are
still few aspects about the experimental tests of Aninthaneni et al. [33, 34] that are relevant and
deserve to be addressed, namely:

- different behaviour could have been observed if a less stiff column (0.70 x 0.60 m\(^2\) in
  this study) had been considered compared to the beam (0.40 x 0.35 m\(^2\)). Since no steel
  plate is embedded in the column as it is in the beam, a less stiff column would not be
  so capable to anchor the steel end plate, and cracking could appear in the concrete
  surrounding the bolts in the column. Similarly to what was depicted in the beams of
  Type-2 connection;

- only the pre-tensioned bolts provide shear strength to these connections. This
  substantially increases stress concentration in the bolts and tensile stresses in the
  column. Consequently, it can cause an increase in the number of bolts embedded in the
  column or an increase in the column dimensions. Thus, it would be interesting to study
  the introduction of a shear key in the column and assess its effect on the shear transfer
  in the connection; and
development of a finite element model to Type-1 connection so a better understanding of the strength mechanisms involved, and the structural behaviour of the connection, could be achieved. A finite element model calibrated to the experimental results could be used to perform parametric analyses of the connection and optimize it (i.e. through the design of smaller ribs in the main ribs of the steel plates to enhance steel/concrete stress transfer).

More recently, Pul and Şentürk [35] studied a beam/column precast dry connection, in which embedded steel plates are used along with threaded bolts. As can be seen in Fig. 4(a), the steel plate embedded in the beam (end plate) is welded to the beam’s main reinforcement and the steel plate embedded in the column (ride plate) is welded to the column’s stirrups. Also welded to the column’s ride plate are high nuts that act as steel threaded ducts to accommodate the bolts and establish the connection (see Fig. 4(b)). The connection was subjected to flexural and shear stresses in experimental tests and the results showed a very satisfactory structural behaviour, similar to the monolithic connection, also tested in the same experimental campaign. For example, the bearing capacity of bolted specimen was approximately 20% higher than the capacity of monolithic one. Furthermore, the shear and moment capacity of bolted joint has increased.

Compared with Type-1 connection studied by Aninthaneni et al. [33, 34], which also achieved a very good performance, one of the differences is that the connection of Pul and Şentürk [35] does not have pretension applied to the bolts. However, this fact does not seem to compromise shear transfer, since the bolts are connected to the ride plate embedded in the column, instead of being anchored directly to the column’s concrete as they are in the Aninthaneni et al. [33, 34] solution. Besides these two aspects, apparently self-balanced in terms of structural behaviour, the connections are designed in a similar way and both achieved good results.
3.2 Wall/wall and wall/foundation connections

Connections between precast wall panels or columns are mainly subjected to compression stresses, easily transferred between the elements without the need of any physical joinery. Consequently, the compression in the connection mobilizes friction and shear stress transfer is also facilitated. For these reasons, the design of wall/wall or column/column connections is not so challenging and complex as the design of beam/column connections. However, most connections between walls or columns still have flexural stress, implying that mechanical joinery is needed.

In this regard, a concrete wall/wall connection proposed by Sun et al. [36] in 2016 is illustrated in Fig. 5, where a robust H-shaped steel connector is used along with high-strength pre-tensioned bolts and top (foot) and bottom (cap) steel units. The H-shape is especially effective in providing buckling resistance to the steel connector, which embraces both sides of the wall. In turn, the pretension in the high-strength bolts mobilized shear strength by friction on the contact surface between the concrete walls and the steel connector. The top and bottom steel units contain steel ducts to accommodate the bolts and have the walls’ main reinforcement welded. The units are placed during casting of the walls and act as confinement for the concrete in the connection zone, along with the stress provided by the pretension in the bolts.

The connection was subjected to a monotonic horizontal load in experimental tests [36], and a very satisfactory behaviour was observed. Failure occurred in the walls away from the connection zone, with a good performance in terms of ductility (with the ultimate measured displacement being 4 to 6 times of the yield displacement). A finite element model was also developed to verify and confirm the load transfer mechanism, failure modes and integrity of the connection. Slippage of the connection due to the surpassing of the shear friction strength was identified both experimentally and numerically for approximately 40% of the maximum load sustained by the connection. After slippage, the shear strength of the bolts, bearing
capacity of the steel parts and concrete compressive strength were the main mechanisms responsible for the connection capacity. Although an advanced (nonlinear) finite element model was conceived and materialized to analyse the connection, the realization of parametric studies was left for further developments. It was concluded that there is still a significant margin for optimization of the connection configuration and dimensions, particularly the steel H-shaped connector.

Besides proposing a solution for a dry connection between wall precast elements, Sun et al. [36] also developed a similar solution for a dry connection between a wall and a foundation. The solution is similar to the one depicted in Fig. 5, in which the bottom steel unit encases the short wall and is embedded on the foundation with ribs to enhance the anchoring bond between the steel and concrete. Cai et al. [37] have also conducted a preliminary study on demountable connections consisting of steel bolts and a steel plates for prefabricated shear walls in low-rise buildings, consisting of three reinforced concrete blocks. The number of steel bolts, the tightening process of the bolts and concrete compressive strength exhibited a significant effect on the overall performance and capacity of the connections. The investigation also identified possible failure modes of the steel bolted joints, including concrete crushing, shearing and tensile fracture of steel bolts, pull-out of steel bolts as well as fracture of steel plates.

4. FURTHER PROPOSED DEVELOPMENTS OF DEMOUNTABLE DRY CONNECTIONS

In the previous section, all concrete dry connections proposed in the literature were detailed and analysed. Moreover, the results obtained in each study were reviewed, through the outline and discussion of the main achievements along with the aspects that need further development as summarized in Table 1, where, for all types of connections, important targets remain unachieved, in the path to make structural engineers apply these solutions in current practice.
While, in some cases, no configuration for the connection has been proposed, in other cases, a solution has been developed but still contains significant margin for improvement, including relevant changes in the configuration of the connection to transfer the stresses more effectively, experimental tests to be carried out, finite element modelling to be implemented or parametric analyses to be made. This section will focus on the first part, that is the configuration and conception of dry connections, since it represents the basis on which more advanced studies would be required. Table 1 presents new configurations and proposed further developments for concrete dry connections between various structural elements. In this context, configurations proposed by the authors of the present paper (Fig. 6 to Fig. 11) will be illustrated and described. Besides the necessary validation by further experimental and numerical studies, it is also relevant to mention that the success of these connections in practice depends significantly on geometric and quality control during the manufacturing phase of the precast elements. Furthermore, availability of a standardization of the position of holes and bolts in different structural elements would facilitate their future reuse in similar applications.

4.1 Beam/column connections

Fig. 6 and Fig. 7 present two schematic proposals for a precast concrete beam/column dry connection that is proposed to include a shear key, which is an aspect outlined in Table 1 as a further development in the conception of a new configuration for this type of connection. With the inclusion of the shear key, no bolts in the compression side of the connection are generally required. Furthermore, the first solution presented (Fig. 6) has additional smaller ribs to the main ribs to enhance steel/concrete bond. This solution is based on the Aninthaneni et al. [33, 34] connection depicted in Fig. 3, which proved to perform well.

The second solution (Fig. 7) is inspired by the connection studied by Pul and Şentürk et al. [35] (Fig. 4), that also showed a very satisfactory performance, with a steel plate embedded in one of the surfaces of the column. The steel plate is welded to the column’s stirrups so a
more effective stress transfer to the column can be materialized. In turn, threaded ducts formed by nuts are welded to the steel plate in the column and accommodate the bolts that are connected to the beam’s end steel plate, which has the beam’s main reinforcement welded. Compared with solution 1, apart from the anchorage system of the bolts in the column, the main differences in solution 2 are the additional row of bolts in the tensioned area (materialized through the existence of openings in the beam’s end to allow placement of the bolts and application of the torque) and the absence of ribs in the beam’s steel end plate. The beam end plate in the two connections shown in Figs. 6 and 7 has another welded plates with ribs embedded into the beam during casting to allow stresses transfer through the connection.

In the study of concrete beam/column dry connections, these two solutions represent different approaches, and, for that reason, they were chosen to be illustrated and described in more details in this section. Nevertheless, other solutions combining the two approaches are believed to be worth investigating as well of being explored in further research works. Furthermore, the two proposals presented in Figs. 6 and 7 may produce more effective performance than those in Figs. 3 and 4 but they are more complex and, consequently, expensive to construct.

4.2 Wall/wall and column/column connections

It was mentioned that the concrete dry connection between precast walls studied by Sun et al. [36] achieved good results, so further developments of this type of connection should only be focused on optimization and design recommendations. For that reason, it seems plausible to consider a similar solution for a concrete dry connection between precast columns, with an H-shaped steel connector (welded to the wall’s reinforcement) and pretensioned bolts. Especially in connections with significant flexural stress, since the H-shaped connector is particularly effective in transferring stresses on the edges of the column section.
In cases where shear stresses are predominant, the inclusion of embedded steel plates in the columns seems to be preferable instead of the H-shaped connector. Fig. 8 shows a schematic representation of that kind of solution, whose configuration follows the same concept of the beam/column connection illustrated in Fig. 6.

4.3 Wall/foundation and column/foundation connections

The precast concrete wall/foundation dry connection assessed by Sun et al. [36] (Fig. 5), equally to the wall/wall connection assessed by the same authors, displayed a very good performance and further developments should only be focused on optimization and design recommendations. In terms of concrete dry connections between a column and a foundation, no research studies could be found so far in the literature. However, and since the type of stresses transferred is similar, the beam/column connection of Pul and Şentürk et al. [35] (Fig. 4) seems to be a solution that could be easily applicable to a column/foundation connection as it showed a structural behaviour similar to the monolithic connection.

4.4 Slab/slab and beam/beam connections

In Table 1, it is mentioned that research on precast concrete dry connections between slab elements is scarce and further research work should rely on the conception and study of solutions that can effectively transfer flexural stress. Aiming to accomplish a solution on that regard, Fig. 9 displays a configuration that includes a shear key sewed by threaded bolts. The bolts are anchored on a steel plate that carries tension stress at the bottom surface of the slab. Compression stresses at the top side of the slab can be either transferred by bearing or preferably by providing a similar steel plate at the top surface.

Stresses acting on slabs can vary significantly between the transversal and longitudinal directions depending on where the slab supports are placed. Consequently, while in one direction the connections can be less stiff, on other direction the same connections can be insufficient to transfer stresses. In Fig. 10, a more robust joint is presented, having on each slab
an additional embedded steel plate with ribs. Those steel plates are welded to the tensioned
reinforcement at the bottom of the slabs. In this solution, the tensile stress is more easily
transferred in the connection, since it is directly transmitted from the reinforcement to the steel
plates. The solution of Fig. 10 can also be applied in structural elements with significant shear
and flexural stresses as beams. However, the presence of embedded steel plates and through
slab bolts may weaken the slab section, leading to failure in concrete.

4.5 Beam/slab connections

Beam/slab dry connections in precast concrete structures should be designed to prevent
slip in the interface (contact) areas between the beam and slab elements, so the flexural capacity
of the composite structure can be the same as in a monolithic structure. To achieve that full
composite flexural strength, shear transfer needs to be effectively transferred in the interface
areas. In this regard, a first sketch for a beam/slab concrete dry connection was divulged by
Aninthaneni and Dhakal [34], where steel angle plates are used along with bolts. In this
solution, shear stress is not directly transferred through the interface area, which is not ideal.

An enhanced connection is believed to be achieved in Fig. 11, where an embedded steel
plate (or connector) with ribs is considered in the interface area. In the presented configuration,
the shear stress is transferred directly along the beam/slab interface, since it is mainly carried
by the embedded steel instead of being forced to make a trajectory through the surrounding
concrete. The conception of the steel plate is inspired in the wall/wall joint of Sun et al. [36]
(Fig. 5), especially in the way it embraces and links to the beam. It also resembles the
beam/column joint of Aninthaneni et al. [33] (Fig. 3) in the design of the embedded ribs. As
can be seen in Fig. 11, the solution depicted also allows the establishment of the slab/slab
connections illustrated more in Fig. 9 and Fig. 10.
5. SUMMARY AND CONCLUSIONS

The review presented in this paper confirmed that the current knowledge on dry connections in precast concrete structures is still very scarce and incomplete, hindering the application of this type of connections in structures. Current practice on dry connections relies traditionally on steel structures and steel/concrete composite structures.

In the past few years, semi-dry connection between precast concrete elements has started to be implemented more frequently, in which reuse is possible after mechanical removal of the cast-in-place parts. Two types of semi-dry connections can be found: dowel shear connection (more common) and moment-resisting connection with continuity bars. Although these semi-dry connections represent a step forward, the deconstruction and reconstruction of the structure elements is time-consuming and not an easy procedure to undertake.

Besides benefits related to time saving and smaller budgets, the achievement of dry connection solutions in precast concrete structures, and its application in the current practice, would have substantial advantages in terms of the environmental impact that the construction sector continuously inflicts. The construction sector is still one of the main contributors to the global carbon emissions and waste storage in landfills. Furthermore, concrete is the most used material nowadays in the construction sector. Therefore, the positive environmental contribution is evident and significant.

Although the current knowledge on precast concrete dry connections is very scarce, some research studies on the subject could be found in the literature. Almost all of them are very recent and the main conclusions derived from their review are the following:

• The main connecting elements include steel plates and bolts; however, the existence of bolts in concrete would reduce the concrete strength as well as create a stress concentration at concrete near the bolts.
The available knowledge focused mainly on connections between a beam and a column. In this context, very good results have been obtained, in which the structural behaviour was similar to that of a monolithic connection. The best results were achieved for non-prestressed joint configurations, with embedded steel plates and pretensioned threaded bolts;

Significant advances were also accomplished for connections between walls and between walls and foundations. A solution proposed in the literature could attain the same behaviour of a monolithic connection. The solution used an H-shaped steel connector (made of welded steel plates) and pretensioned threaded bolts. In wall/foundation joints, the H-shaped steel connector had ribs and embedded in the foundation.

For other types of connection (i.e. column/column, beam/beam and beam/slab connections), no research could be found in the literature. For foundation/foundation and slab/slab connections only preliminary studies were published.

Numerical modelling and simulation to explore load transfer mechanism, failure modes and integrity of demountable connections are very limited. The main challenges are in the modelling of compatibility of various elements as proposed for demountable connections, including concrete elements, steel plates and bolts. Such numerical models need to be calibrated to the experimental results and, eventually, used to perform parametric analyses of the connection and optimize the connection configuration and dimensions.

Although the initial cost of dry demountable connections would be higher than that of monolithic or semi-dry connections, the life cycle cost analysis would significantly highlight the potential benefits of demountable connections. Such connections would facilitate the future reuse of structural elements at the end of their life, potentially
achieving a significant reduction in embodied energy of structures, saving landfills
as well as giving the clients the benefit of retaining the value of their assets. However,
no life cycle cost analysis studies of demountable connections were found in the
literature.

Despite the advances already made on the study of precast concrete dry connections, the
current state-of-the-art is still far from being sufficient to allow engineers to design structures
containing these connections. Therefore, future research on this subject is encouraged, possibly
based on the proposed solutions in this paper.

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<tr>
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Fig. 1. Dowel connection between a column and the foundation of a reinforced precast concrete structure: (a) before the grout injection; and (b) after the grout injection. Reprinted from Metelli et al. [26].
Fig. 2. Moment-resisting semi-dry connection, with welded continuity reinforcement, between a beam and a column of a precast reinforced concrete structure. Reprinted from Xiao et al. [27].
Fig. 3. Three types of concrete beam/column dry connections with pretensioned threaded bolts and a steel end plate: (a) outlook; and (b) detailed view. Reprinted from Aninthaneni et al. [29].
Fig. 4. Concrete beam/column dry connection with embedded steel plates and threaded bolts: (a) view of the disassembled form; and (b) view of the assembled form. Reprinted from Pul and Şentürk et al. [30].
**Fig. 5.** Concrete wall/wall dry connection with a horizontal steel connector and high-strength bolts. Reprinted from Sun *et al.* [31].
Fig. 6. Schematic representation of a beam/column concrete dry connection – solution 1.
Fig. 7. Schematic representation of a beam/column concrete dry connection – solution 2.
Fig. 8. Schematic representation of a column/column concrete dry connection.
Fig. 9. Schematic representation of a slab/slab concrete dry connection – solution 1.
Fig. 10. Schematic representation of a slab/slab concrete dry connection – solution 2.
**Fig. 11.** Schematic representation of beam/slab concrete dry connection.