Demountable reinforced concrete structures: A review and future directions

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ABSTRACT: Consuming about 60% of natural resources, construction industry recently has been under a continuous pressure to ensure an efficient consumption of natural resources. Recent decades have witnessed some valuable steps toward making the construction industry more sustainable. This includes the trials to change the linear life cycle model to cyclic one by the consideration of the 3Rs; recycling, reusing and reducing to help in closing the material loop. However, recent studies have showed that the reason for demolition is not really the end-of-life span of structures but actually the lack of adaptability, also, demolition and recycling demand huge energy. So that the possibility to dismantle/ disassemble/ demount an RC building in order to salvage its material for reuse has been under focus. This requires the design for deconstruction “DfD” to close the loop of materials similar to cradle-to-cradle model where “waste” is turned into “feed” in comparison with cradle-to-grave thinking. The structures should be designed as a prefabricated structures and elements should be joint in dry way. The current paper will review the concept of structure demountability in the context of the recent advances in building systems and the ongoing researches in the area. Some early real cases of demountable structures in Europe will be discussed and challenges including design requirements and future directions will be highlighted.

KEY WORDS: Reinforced concrete; Demountable; Construction sustainability; Cradle to cradle; Design for Deconstruction.

1 INTRODUCTION
The construction industry requires billions of tons of materials and this results in a huge consumption of natural resources where it consumes about 60% of natural raw materials. Also, construction industry is responsible for high rates of CO₂ emissions especially those associated with cement production. Furthermore, it is responsible for billions of tons of waste due to demolition [1]–[4]. This is because the material flow of construction is characterized by linear open process that has materials, energy and water as inputs and has waste, emissions and by-products as outputs. However, over recent decades and with the scarcity of land and landfill, a great challenge emerged regarding ensuring efficient consumption of natural resources and, hence, there was a pressing pressure to make construction industry more sustainable. Material sustainability depends upon closing the material loop and making the material life cycle circular instead of linear by collecting the wastes, processing them and then reusing them. During the last few decades, there has been extensive works done on waste treatment and recycling in construction industry.

2 RECYCLING AND DEMOLITION
Closing the loop requires two essential stages in the process; demolition and recycling. To assess these two steps in the lifecycle of a building, it is required to look at their contribution to the embodied energy because when considering life cycle of a building, both embodied energy and operating energy need to be counted where embodied energy should include energy consumption during all processes of production, on-site construction, and final demolition and disposal.
The longer a building in service, the smaller the embodied impacts are per year of service [5]. A study to understand the relationship between structural materials and building longevity found that the reasons for demolition ranged from area development, lack of maintenance, and the building are no longer suitable for intended use [6]. These results means that durability was not the main issue in many structures and the demolition in many cases is due to poor adaptability rather than due to a durability issue. Such results are so critical in the way we deal with the construction life cycle, embodied energy and structural durability.
It is stated [7] that demolition was responsible for 90% of all construction and demolition waste in 2000 and these waste can be recycled. However, recycling consumes massive energy especially what relates to crushing and grading. Demolition reasons and recycling requirements show that durability may not be the best strategy to increase building life. Such strategy in closing the loop is still far away from Europe’s new strategies for efficient resource usage [8]. There is still a need to reduce the embodied energy and carbon emissions of the construction energy and extending the life of raw materials

3 DEMOUNTABLE REINFORCED CONCRETE STRUCTURES
The aforementioned concerns towards sustainability of construction, together with the need to save the huge energy that is consumed in demolition and recycling, led to an innovative thinking in dealing with the source of the problem by increasing the service life of buildings, and hence, decreasing the embodied energy per year of service. This can be reached by giving the structure the possibility to be dismantled/ disassembled/ demounted in order to save its material for reuse.
So the terms “Demountability and Deconstruction” emerged to describe the construction technique or method that
uses structural connection enabling the structural parts to be demounted with no or little destruction and to be reused in other structures “dismantling not demolishing” (Figure 1) [4], [6], [7], [9]. This method helps salvaging building materials and mitigating the environmental impacts by reducing the amounts of wastes and saving the energy used in demolition and recycling. It is known as “construction in reverse” [4].

Figure 1. Selective removal of Palast-der-Republik in Berlin 2007, [9].

The simple idea of demountable structures can be explained by Figure 2 that shows a three dimensional structure created from high fibre reinforced concrete beams that hold each other up through simple support bindings called spatial reciprocal frame [10]. This building technique allows the disassembly of the elements and reassembling them into different forms.

Figure 2. Three element junction, Spatial Reciprocal Frame, high fibre reinforced concrete [10].

Deconstruction is a modern terminology for old practise. Due to their migratory patterns, Native American built their shelters in such a way to facilitate future disassembly [5]. Such concept was applied by different nations to different types of structures, however, this is so challenging when dealing with concrete/Reinforced concrete (RC). The prefabricated concrete assembled by structural connection enabled the possibility for demountable reinforced concrete structures. During the last decades there were some cases for demounting concrete/Reinforced concrete structures. The characteristics of demountable construction especially that relates to the possibility for rapid enlargement or reduction of the building and the relocation of the building to another site makes it preferable in structures which consist of many similar parts such as solar and wind power plants and carparks which requires such flexibility. Reviewing the literature shows a connection between demountable structures and carparks. One of the oldest officially recorded cases was the demounting of RC garage building which was recorded as a US patent in 1973 [11]. Another patent was recorded in 1980 [12] for a multiple level building structure utilizing a first set of precast reinforced concrete modules having integral supporting legs separated by a second set of precast or in situ cast reinforced concrete modules. One of the oldest reported real cases was reported in 1988 [13] which was claimed to happen in 1971. It was not intended case and it included the demounting and remounting of eleven story building and it is thought that demounting of the building was successful because the designer was involved in the demounting process. During the last three decades, there have been more drives toward the application of demountability in RC structures as an essential type of structures where the benefits exceeds the environmental effects to social and economic effects by lowering the cost of material, extending the life of raw materials, creating jobs for unskilled workers, creating of brand new market for salvage material and getting the maximum benefits of precast concrete such as increasing the speed of construction and increasing the precision for structural elements that are manufactured offsite [4], [5].

3.1 Prefabricated RC for demountable RC

Not all RC systems are ready for demounting because of the connections where some systems use connections which are grout with mortar. There should be no or almost no cast in place concrete elements and “wet connection” where grout is used to fill the splicing closure should be avoided and the structure should be designed as a prefabricated structure [14]. Prefabricated structures can be demountable and remountable if the connections are designed and detailed in a proper way as “dry connections” and made as simple as possible so that human errors in the building site are reduced to a minimum [13]. Dry connections, or dry joints, generally achieved with the use of dowels, anchor rods, threaded bolts, steel billets, steel plates and steel angles. Many researchers have proposed dry connections in different configuration such as the usage of steel angles/plates with high strength friction grip HSFG bolts [13]. Others introduced a newly developed dry joint between prefabricated slabs using aluminium foam that has been produced in the shape of Al-bars (Figure 3) [9]. The Aluminium foam is lightweight, stiff enough to provide the shear transfer and should be fire resistant and air tight [14]. Such researches would promote demountability as an advantage of prefabricated concrete which has not been fully explored.

Figure 3. Demountable joint, two slabs with the Al-foam [9]
3.2 Design for Deconstruction

Although there are some cases where demounting and remounting occurred without intention, demountable construction requires dealing with the problem at source, which is usually at the design stage by designing for deconstruction. Design for Deconstruction/Design for Disassembly (DfD) is essential to close the loop of materials, similar to cradle-to-cradle model where “waste” is turned into “feed” in comparison with cradle-to-grave thinking. The application of design for deconstruction, design for durability, and design for adaptability can help in extending the life of structural materials where the end life scenario of RC structure is determined by the way in which the structure has been designed, constructed and built [1], [6].

The demountable systems form closed systems where only elements from the same system can be connected to each other and this requires that architectural demand to be limited [14]. The design adjustments for demountability require the minimisation of monolithic connection usage and contact interfaces must be used for links. The path of force is quite clear and transparent and there are many parts in the structure where most parts are statically determined, hence, the design for DfD should focus on simplicity and repetition [8] [13] [6] [15]. Also, the design should consider the procedures for reusing the different structural elements. Key principles of DfD were summarized in [7] as follows: proper documentation of materials, design connections and joints to ease dismantling, separate non-recyclable, non-reusable and non-disposal items, design simple structures, and design reflecting labour practices, productivity and safety. Such design considerations in DfD face resistance as they require a change in philosophy specially that relates to the architect demands to be limited. Also, load bearing structures would be questioned after first cycle and information about other performance criteria would not be available anymore.

3.3 Industrialized, flexible and demountable (IFD) building systems

The need for demountable structures to be disassembled and rebuilt requires a production process that is simplified with a high level of quality ‘industrialize’ and with the ability to accommodate functional changes without destruction ‘flexible’. Here comes the new industrialized, flexible and demountable (IFD) building systems where it allows making building as flexible as a kid toy game “Lego” [16]–[18]. The Basic Philosophy is that components are standardized and produced in a controlled environment as durable of high quality and are joined in dry joints. Systems are flexible to meets future requirements and changes without destruction and with little effort [18], [19]. Figure 4 shows The NEXT-21 prototype in Osaka as an example of the IFD systems.

Figure 4. IFD building system example; NEXT21 in Osaka [19]

4 REAL EXPERIENCE

Netherlands had some early real efforts and, hence, real cases of demountable structures. The Dutch Centre for Civil Engineering research, codes and specifications CUR formed a research committee on demountable construction in 1985 [11]. There was a construction innovation program to challenge the construction industry to improve their overall performance. This encouraged the industry to develop some of market demountable systems that had been applied in the following decade. Figure 5 shows a demountable structure in the mounting phase.

Figure 5. Mounting state of demountable structure, Netherland [11]
There are five systems on the market named as the Mxb-5 system, CD-20 system, SMT system, Bestcon-30 system and Moducon-2000 system. Each system has its own specifications such as structural element types, dimensions, loading capacity, etc., and, most importantly, the connection details. Figure 6 shows different connection illustrations of two different systems. The reader is referred to [14] for more details on the these systems and their connection systems. Although these systems are not seismic resistant and have some issues in replacing, they give an indication on the possibility for adapting demountability among construction industry across the whole European construction industry which could be feasible if some requirements are fulfilled. After three decades, more advances emerged and more requirements are needed to promote the adaptability of demountable structures, such requirements and challenges will be presented in the following sections.

![Figure 6. Connection types of some market system [13].](image)

5 RECENT RESEARCHES

There were many attempts to apply demountability to structures, however, most of these efforts were restricted to steel structures. The problem of applying demountability to concrete reinforced concrete has recently taken into consideration by many researchers and there is ongoing research to facilitate and promote the application of sustainable demountable construction. In 2017, The Institute of Civil Engineering and Environment (INCEEN) at the University of Luxembourg was part of it to develop new scientific and technical methods for sustainable buildings. [15]. The extent to which a building could be deconstructed right from the design stage was considered in [20] by developing a Building Information Modelling based Deconstructability Assessment Score (BIM-DAS). Lots of researches targeted the connection as being the key toward the application of demountability in reinforced concrete structures. A research focused on experimental verification of demountable precast column structure and its demountable steel joints [21]. Another one proposed a shear connection by attaching the concrete slab to a steel frame with semi-rigid bolted connections using high-strength friction grip bolts where tests have been done on full scale joints that demonstrated a significant ductility [22]. The structural behaviour and enhanced loading capacity of transversely confined precast reinforced concrete deck slab with deconstructable post-installed friction-grip bolted (PFGB) shear connectors was investigated by [23] and then a finite element model of the deconstructable composite deck with external confining systems and PFGB shear connectors was developed. Other demountable beam-to-column composite joint systems were proposed recently in [24] and [25]. Experimental programs also are being carried out in parallel with theoretical studies to investigate the effects of various parameters on the behaviour of demountable connections [26] [27] [28].

6 NEW TRENDS AND CHALLENGES

There are many challenges facing the application of demountable structures beside the development of dry strong connections. Seismic considerations need to be considered in the designing phase when designing the structure and the joints. Aslo, the designer should consider the disassembling phase during designing and not only the erection phase, the structure must be optimised in terms of materials ageing and energy consumption in an integrated way within an overall building concept [15]. Another challenge comes from the fact that demountable systems are closed systems where only elements from the same system can be connected to each other, hence, an effort should be made to allow for the possibility of upgrading as well as the possibility for partial demounting. Installation for heat, water and communication into the structural elements should be considered and treated to ease dismantleing [14]. Circular economy market needs to be installed to provide schemes and solutions for the deconstruction, transport, condition assessments, temporary storage and reuse of whole structural elements [15].

7 CONCLUSION

For attaining an efficient resource consumption and achieving sustainability in its best achievable version, Demountable Reinforced Concrete Structures should be adapted in the construction industry. It has many advantages over many other types of structures. It saves resources and energy, allows for easy and fast modifications and it can be of low cost once the market exists. Although there is a continuos developments in the field of concrete technologies, the link of these developments to the end-of-life phase is still missing. The application of demountable structures needs a full cooperation between research and industry to overcome the obstacles and push its application forward. More research is needed to facilitate the application of demountable constructions but acceptance and implementation are also of equal importance at the moment.

REFERENCES
