Functionally Gradient Concrete // Resource- and emission-reduced concrete building construction system for NZ - The development of a seismically resistant joint for a functionally graded concrete wall-to-floor connection

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Abstract. Concrete is known to have a large carbon footprint; however, its versatility and durability are unparalleled. These qualities pertain to the usefulness of concrete in an ever-increasing population, and therefore demand our attention. By optimizing and improving the performance of concrete through innovative technologies, such as functionally graded concrete, the carbon footprint can be reduced. In construction, the weight of a conventional concrete structure accounts for approximately 70% of a building’s total mass. In comparison, functionally graded concrete (FGC) is 50-60% lighter, accounts for reduced emissions (45-60%), and has improved insulative properties. These factors are achieved by its increased porosity and efficiency of material. Additionally, in comparison to a conventional concrete system, less raw material would be needed to achieve the same structural requirements and therefore less resources would be required. By varying its density, FGC creates a purely mineral, multifunctional, mono-material element that is fully recyclable. Investigations into implementing FGC as a building component in seismic areas have not yet been carried out. The development of a seismically resistant joint for a FGC wall-to-floor connection is necessary due to seismic requirements present around the world. The project presents a review of existing seismic resilient connection technologies, their classification to small scale and largescale building typologies, and the development of concepts for FGC seismically resilient wall-to-floor connections.

Keywords: Concrete connections, precast concrete, case study analyses, new connections, development, functionally graded concrete, seismic resistant joint, wall-to-floor connection.
1. Introduction

This paper presents a review of contemporary methods for connecting precast concrete components, specifically seismic resistant wall-to-floor connections that are used across Europe, the U.S, and New Zealand. The criteria of this search included; connection form typology, origin, building typology, assembly and seismic resistant design. After reviewing the various methods of connecting precast wall and floor elements, a formulated design approach was applied to a functionally graded concrete (FGC) wall-to-floor connection example. The intent is to comply with current building regulations. Functionally graded concrete is based on technology -called micro-gradation- which allows for an inhomogeneous concrete distribution. Because the interior foam structure is highly insulative the system can therefore be employed to achieve single-layer, monolithic design outcomes (see figure 1). Components, such as floor slabs, can use up to 62% less material overall in comparison to conventional concrete [1]. The implementation of FGC has the potential to decrease carbon footprint of concrete manufacturing and to allow for concrete construction on a larger variety of site conditions due to a 42% reduction of weight, while still providing the typical benefits of concrete [2]. The development of suitable seismic resistant connections for FGC components is necessary due to seismic design requirements in many areas around the world.

The aim of this study is to propose a novel design for a functionally graded concrete wall-to-floor connection. Currently there are no examples within the body of research of seismic resistant connections that have been developed specifically for FGC components. This gap in the research of FGC is the focus for this paper. The desired outcome would be to achieve and realize a conceptual detail design that has the potential to be an acceptable solution under the New Zealand Building Code (NZBC). The realization of such an outcome would allow for FGC to be considered as potentially new material for use in New Zealand construction. In turn, this would also present the possibility for FGC to be considered in other earthquake-prone countries around the world.

This paper reviews contemporary methods for connecting precast concrete components, in specific seismic resistant wall-to-floor connections that are used across Europe, the U.S, and New Zealand. Academic and professional publications and guidelines gathered through relevant databases with parameters for selection were used in this literature review. These parameters were: connection form typology, origin, building typology, assembly and seismic resistant design. After reviewing the various methods of connecting precast wall and floor elements, a formulated design approach was applied to a FGC wall-to-floor connection. The conceptual designs of connections, that were combined to create new details, work as a starting point for the design of a seismic resistant functionally graded concrete wall-to-floor connection.
2. Literature review

2.1. State of the art

2.1.1. Connection form typology. Four commonly used arrangements for wall-to-floor connections used in prefabricated and in-situ concrete construction were identified through an initial search for connection examples, as are indicated in following figures 2, 3, 4 and 5.

**Figure 2.** Flush connection  
**Figure 3.** Recessed connection  
**Figure 4.** Top-through connection  
**Figure 5.** Corbel connection

A - The floor plate sits flush against the wall component and is connected either in-situ with a topping layer, or with steel fixings. The need for additional elements to support the floor such as steel angles or brackets are required for the flush connection. The methods for fixing such steel fixtures into the precast components vary from cast-in, to bolting on site, or with a topping layer of concrete. Each method requires specific attention to ensure a robust and safe fixing into the concrete components. It is achieved with consideration to deformations experienced during an earthquake, especially when loads are transferred via the steel connections, making such details potentially vulnerable if poorly designed. If successful however, the flush connection is a relatively flexible connection which can be an advantage during an earthquake (see Fig. 2).

B - The recessed connection is similar to the top-through connection, where the floor plate is sitting directly on the wall and the second wall of the upper floor sitting on top of the floor plate. However, the floor plate is instead recessed halfway into the wall panel, giving the floor plate stability regarding shearing forces, serves with stability regarding horizontal pull forces, and has sufficient rigidity to provide resistance to bending actions. Another advantage of the recess is the increased weather tightness of the joint. (see Fig. 3).

C - The Top-through connection is defined as the floor plate is bearing directly and fully on the wall. It is formally characterized by a direct transfer of the bearing loads through the wall component. The wall of the next floor section is placed on top of the floor plate which provides weight stability regarding bending moments. This connection type does not rely only on any additional connection elements such as steel angles or brackets (see Fig. 4).

D – The floor plate sits flush against the wall and on the other hand, the floor plate is sitting on a corbel, through which the bearing load of the floor plate is transferred into the wall. The position of the floor plates in relation to the walls is clearly defined and aids with stability regarding horizontal pull forces. This connection type is often used in large buildings with long floor spans and multiple floors. This is because the corbel connection can bear heavy loads and the assembly process with prefabricated concrete elements can be done with cranes and be precisely positioned on site (see Fig. 5).

2.1.2 Defining of relevant parameters
The parameters described below were used to identify suitable connection case studies. The five parameters were selected due to their relevance to the subject of precast concrete construction as well as the New Zealand building stock. The five parameters were:

*Origin of examples*
This parameter is the broadest due to the wealth of expertise that can be found around the world. Examples gathered come from New Zealand, Europe and the U.S. Having the research based in New Zealand has also provided the chance to look at contemporary construction drawings of realized projects throughout Auckland.

**Building typologies**

The building typologies accessed include: small scale residential projects (maximum two floors, smaller floor spans) and large scale commercial or residential projects (more than 2 floors, larger floor spans). These two typologies were selected because of their different requirements of bearing loads resulted of small or high floor spans and weights. This causes varying structural design solutions and therefore a variety of connection designs. By studying this range of building typologies, it is possible to see how wall-to-floor connection details may differ according to the structural requirements of each project.

**Assembly**

Whether connections between precast components are dry, and fixed with steel components on site, or in-situ and fixed by pouring any additional concrete or grouting. This criterion is important to consider due to the differences in design around connection points.

**Seismic resistant design**

All of the examples found are intended to demonstrate how precast concrete construction can be achieved while meeting seismic design requirements. This criterion allows the examples to be relevant to the design of a potential FGC wall-to-floor connection intended for future use in New Zealand or other seismically active regions.

2.2. *Selection of details to be investigated*

The examples shown come from a broad search done through academic and professional resources, as well as a handful of building project drawings that were accessible to the authors in New Zealand. However, it is important to note that the examples given are indicative only and are intended to show a variety of ways of connecting precast concrete diagrammatically, to help build a picture of established practices for seismic design with precast and in-situ concrete around the world.

Table 1 and 2 show the selection examples of wall-to-floor connection details gathered as part of the literature review. The parameters that were established for this search were: connection form typology, building typology, assembly (wet or dry connection), country of origin, and seismic resistant design, as described above.

**Table 1.** Selected example of wall-to-floor connection details for small scale residential building typology with parameters: connection form typology, fabrication type, country of origin, and seismic resistant design (4 [3], 5 [4], 6 [3], 7 [5], 2 [4], 8 [6]).
Table 2. Selected example of wall-to-floor connection details for large scale residential & commercial building typology with parameters: connection form typology, fabrication type, country of origin, and seismic resistant design (9 [7], 10 [8], 11 [9], 12 [10], 13 [11] 14 [5], 15 [9], 16 [9], 17 [6], 18 [6]).

| Large scale residential & commercial |
|--------------------------------------|
| ![Connection Details](image)         |

Key:
- Wet connection
- Dry connection
- Chosen examples
3. Results

3.1. Criteria used for assessing connection suitability for adoption with FGC Assembly

This criterion refers are dry or in-situ. Both types of connections are used in seismic resilient structures depending on the local site conditions of a given project.

Seismic performance

This criteria is the method in which the connection achieves the seismic resilience it is designed for. This criterion is necessary to understand how conventional practices can be adapted to the design of a FGC component that is seismically resilient.

3.2. Review of existing connections

The case studies presented in this section are derived from an initial search into seismic resilient precast concrete construction examples and can be seen in table 1 and 2. As described earlier, the focus of the search within this category of construction was on examples of wall-to-floor connections, not excluded wall-wall-floor connections. The overall composition and general function of each connection is described, as well as the assembly of each example. Both wet and dry connections were part of this review, however all of the examples discussed in the next section have a wet, or in-situ, component to their assembly. The specific case studies presented in this section were chosen due to their characteristics being deemed most adaptable to that of an FGC wall-to-floor connection.

3.2.1. Example 1 – Wall to floor in-situ connection with steel reinforcement Assembly.

As with an in-situ system, the formwork and reinforcement for the bottom walls are erected first. The floor component can then be placed in-situ on top of the walls, followed by the second level of walls connected again with steel reinforcement by in-situ concrete. This system is also achievable with
precast wall and floor components, in which case a grout layer at the interface could connect the components.

**Seismic performance**

This example is intended to be assembled in-situ (on site). This decreases the ductility of the connection between the components, increasing the likelihood of being damaged by seismic movement. However, if the reinforcing details are well designed, the connection can still be relatively ductile regardless of whether the joint is in-situ or a dry joint.

### 3.2.2. Example 2 - Precast wall-floor connection with in-situ top layer and steel angled fixture Assembly

![Figure 7](image)

This example shows the precast floor being connected to the wall with an angled steel fixture that is fixed to another cast-in fixture within the wall. Floor reinforcement is connected into the wall panel using a threaded insert, after which a concrete topping layer is poured.

**Seismic performance**

In this example, the dry steel connection provides flexibility to accommodate for joint deformations during earthquakes, while the topping layer provides a connection between the floor and wall that is critical for diaphragm strength and seismic load paths [12]. The example is for a small-scale residential typology application (see table 1) but has a higher structural performance than the other examples in the small-scale building category. Therefore, it could be located in both categories.

### 3.2.3. Example 3 - Precast wall to in-situ post-tensioned floor connection Assembly

![Figure 8](image)

This example shows an in-situ or precast floor being connected to a precast wall component. The floor component is supported by a steel angle and a tendon connects the floor to the wall horizontally. This is an unbonded post-tensioned tendon which could be achieved for both in-situ or with precast components.

**Seismic performance**

This is a highly ductile example in that the steel angle does not have pins that fix the components in place, but instead acts to support the floor while allowing movement between the components at joint deformations occur. The post-tensioned tendon provides a load path for diaphragm actions and ensures
that the components return to their original position after movement has occurred during an earthquake.

4. Outcomes

New seismically resistant FGC connections

This section features the outcomes of conceptual designs for a FGC wall to floor connection, each of which are based on the analyzed examples derived from the literature review, as can be seen in table 1 and 2. Modifications, combinations or adaptations were added where deemed necessary from other examples in the table. The purpose of this was to act as an initial step into the design process of this connection. This section shows conceptual designs of connections that were combined to create new details, which work as a starting point for the design of a seismically resistant functionally graded concrete wall-to-floor connection.

4.1 Design 1 - FGC top-through dry connection with steel bolt and upper angle

Inspired by the example 1 connection, “Wall to-floor in-situ connection with steel reinforcement” the focus became the transformation of this connection into a dry, prefabricated system.

**Assembly**

In this design, the bottom FGC walls are erected first, after which a vertical steel bolt can be inserted into their tops. Such a connection can also be seen in examples number 9, 8 and 18 (see table 1 and 2). The floor component containing a steel angle fixture can then be placed on top of the walls, followed by the second level of walls. Finally, the wall and upper floor components can be bolted in place, activating the joint.

Unlike the Halfen rail connection, that can be seen in example number 7 (see table 1), Design 1 only uses a single steel bracket connection. The prefabricated Halfen joint is a linear fixing and is intended to solely bear the whole floor plate weight. This example however takes advantage of the compressive strength of the precast wall component for bearing the load of the floor plate, while the steel bracket improves ductility and stability between the components. Further investigation into establishing a clear mechanism for seismic load transfer will be conducted in order to determine whether this design may be used as part of a structural lateral load resisting system. This is due to the bolted connection not being completely sufficient for high seismic loads on it’s own.

**Seismic performance**

This design is intended to be simple to be assembled on site, while providing an element of ductility between the FGC components to avoid them being damaged by any movement. The steel fixtures are intended to absorb most of the seismic forces. By having all of the steel components accessible, they can be removed and replaced if damaged during an earthquake. The design of the density throughout the FGC components is also essential, as is shown in figure 9, and is higher around the areas of stress, as well as the outside faces of the components in which the reinforcement is placed.
This connection has a high capacity for flexibility and deformation but is lacking in ductility due to there being no reliable strength or yielding mechanism.

Functionally graded concrete connection optimisation

In this design, the quantity of steel used for the connection within the concrete structure is reduced by instead allowing the compressive load to be borne by the wall panel below. However, further investigation will be conducted as to the strength of this connection in regard to the transfer of seismic loads from panel to panel in this way. The bracket is fixed in place on site and not cast into the wall or floor panels due to ease of serviceability after any damage may have occurred during an earthquake. With this design the authors intend to simplify the connection in advantage of the properties of FGC.

4.2 Design 2 - FGC precast wall to post-tensioned floor connection

The new connection is an adaptation of example number 2 “Precast wall-floor connection with in-situ top layer and steel angled fixture [4], and example number 3 “Precast wall to in-situ post-tensioned floor connection” [10].

Assembly

The use of a steel angled fixture underneath the floor plate is taken from a residential project in Auckland (Example 2) and is commonly used in precast concrete construction. The steel angle is used to transfer vertical bearing loads from the floor. Thus, the connection remains flexible, while the tendon provides a load path for diaphragm actions. The unbonded post-tensioned tendon is an adaptation of example number 3 which is a construction detail for large buildings. The tendon is inserted through the components, unbonded in a sheath tube and tensioned to provide both strength for diaphragm load and self-centering to the joint.

Seismic performance

This is a highly ductile connection in that the steel angle does not have pins that fix the components in place, but instead acts to support the floor, allowing movement between the components.

Adaptability to a functionally graded concrete system

The new system is well adaptable to a FGC system as the steel fixtures needed for such a connection could be cast into the wall and floor components during fabrication. The density of the FGC may need to be increased around these areas to support the forces that can occur there. The topping layer of concrete as in example 2 is undesirable because it would mean that the system would not be a solely FGC system, but a composite concrete system. The disadvantage of reinforcement threaded into a shoe, like shown in example 2, is that there may be an increased chance for the shoe to be pulled outwards and cause cracking in the concrete during an earthquake. Increasing the density of the FGC
in this area, as well as deepening the placement of the shoe connector within the wall, would help to
decrease this risk.

The adaptability of the example 3 “Precast wall to in-situ post-tensioned floor connection”,
to a FGC could be achieved if the design of the components ensured that the right balance of porosity
and density were achieved around the areas of the structure that experience the most stress. For
example, density would need to be higher around the area where the joint between the two
components and where fixing occur, as well as areas surrounding any reinforcement and the sheath
tube in which the tension rod runs through.

5. Discussion
All the connection concepts presented in this study have characteristics that may be suitable for use in
the design of a FGC wall-to-floor connection. If in-situ components are used to activate connections, it
would be more difficult to do so with FGC because of its typical prefabrication process. So far, these
examples only used dry connections as design principle due to simplicity and efficiency in
construction and assembly. This limitation needs to be explored, so that a full picture of conventional
wall-floor-connection methods can be understood and applied, depending on the structural design
requirements be hypothetically met.

The main reason for using dry connections in this study is that most of the in-situ joint types
accessed in this study create a more rigid connection which may become brittle in the event of an
earthquake. However, a higher degree of ductility, flexibility and serviceability of a joint may be
achieved with dry connections such as those shown in the outcome of the two new designed
connections, where various steel fixtures are used to connect the precast components instead. This is
not to say that in-situ connections may not yield positive outcomes also, as they can provide strength,
but need to be applied alongside a mechanism that can accommodate deformations.

6. Conclusion and Outlook
The aim of this study was to provide wall to floor connection cases for the use of FGC within
seismically active environments. Advantages and disadvantages of the case studies presented in the
literature review were discussed, followed by an analysis in which the study offers potential pathways
for the design of a seismically resilient FGC connection.

The benefit of replacing the conventional precast components with FGC would be a decrease in
both the weight of the structure as well as the amount of concrete used in a project, as is shown by the
differing porosity throughout the section drawings of the two new designs. The porosity of FGC is
linked to the reduction in the emissions of greenhouse gases through a decreased demand on raw
materials and an increased efficiency when using concrete. Other potential industry applications of
FGC include:

1. FGC can be used as the main structural system for building typologies ranging from small-
scale residential, to large-scale commercial and public projects.
2. As FGC is a prefabricated technology, its production and use has the potential to be
assimilated into already existing precast concrete manufacturers, which would be
beneficial to the concrete construction industry overall.
3. In lieu with building thermal performance requirements around the world, FGC
components have the capacity to provide higher insulative properties due to their porosity.
4. Due to the single-layered construction approach of FGC, the requirement for cladding and
interior lining can be negated when erecting exterior walls. This would make the
construction process faster and simpler on site.
5. When a FGC building component needs to be recycled, the process is made easier by the
single-layered assembly which doesn’t have other elements and wrappings glued on to it.
Furthermore, a reduction of masses in seismic zones decrease the amount of horizontal loadings
activated by an earthquake. The seismic performance is highly dependent on the whole structural
design system of the building. The position of steel reinforcement is predicted and roughly marked into the drawings. This demanding task will be addressed in the next research steps of this project by looking to further existing examples. Therefore, the next is to evaluate the connection types related to an existing built project, and then to modify the precast technology and the wall-floor connection details into a FGC system. The second step will be to create a scale 1:1 mock-up and test this connection regarding structural design forces and seismic activity in a laboratory.

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