THE NEW ZEALAND CONCRETE INDUSTRY
CONFERENCE 2015
Rotorua Convention Centre 8-10 October

THE DESIGN AND CONSTRUCTION OF A CAST IN SITU CONCRETE HELICAL STAIRCASE

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SUMMARY

An examination of design and construction techniques to cast a complex three dimensional helix in concrete.

INTRODUCTION

The Cullen helical concrete stair is the vision of Stevens Lawson Architects with structural design by Sullivan Hall and construction executed by Bannan Construction. The construction consists of 8 cubic meters above ground and a further 4 cubic meters of podium and foundations below. Founded on the underlying bedrock, the helix gracefully extends from the ground to the first floor of the dwelling. A total of 1800kg of reinforcing arranged to accommodate the stresses generated has been painstakingly crafted to fit within the 150mm wall thickness, plinth and foundations. The culmination of all this effort is a piece of strikingly beautiful concrete.

Figure 1 – completed staircase

ENGINEERING DESIGN

Modern design tools such as finite element packages have been able to simplify the possibility of analysing complex concrete shapes. Analysis however is only part of the solution. There is an array of other components that require the attention of the engineer. This project demanded a high level of attention from tolerances of fitting in reinforcing that dictated bar size, to appreciating the pour sequence and how it may impact on the design. The primary objectives however could be reduced to two simple objectives:

- It had to be strong enough (Ultimate limit state)
- It had to be beautiful (serviceability limit state + methodology)

The first objective is the most definitive to complete. Finite element packages can generate both meaningful demands and capacities. While a number of techniques were used to analyse this helix, the most visually rewarding was the design outputs from Robot. Colour displays of stress concentration and reinforcing content unlocked the areas of primary concern. Refer figure 2. Despite this however, the numbers were re-checked by completing a pseudo strut and tie arrangement.

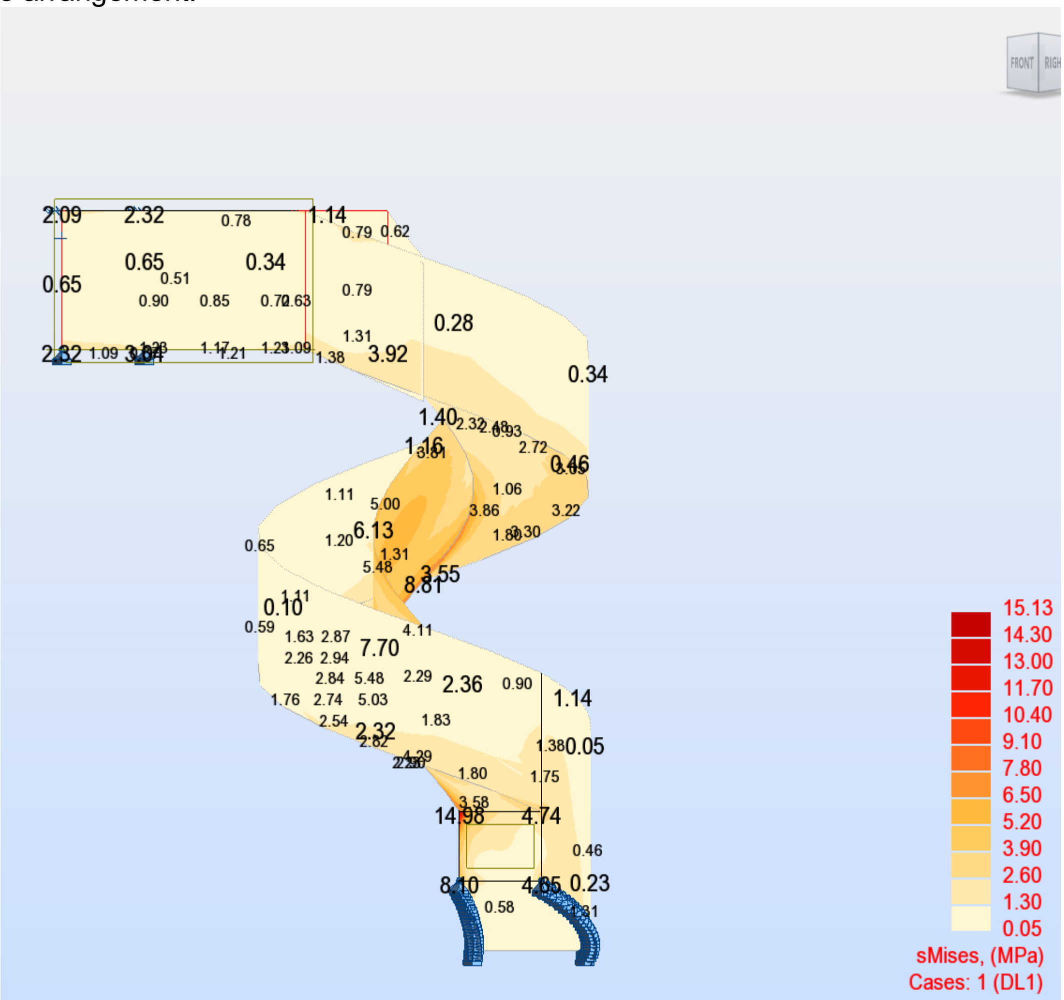

Figure 2 - Stress Analysis - Dead load

Initially the model was constructed with pins (fixed spatial position, free rotation) at ground and second floor level. This resulted in peak moments and stresses at the point of fixing at the second floor level. The model was refined to have pins at the base and springs at the top of the handrail at the second floor level. This alleviated the stress concentration at the supports but increased the deformation in the helix. A range of spring stiffness's were examined to understand the sensitivity and impact of fixing points.

There were a number of design limitations imposed by the partially constructed house that were not envisaged, they included the physical space in which to facilitate the connection on one side to the upper wall and the impact of downpipes in the other side.

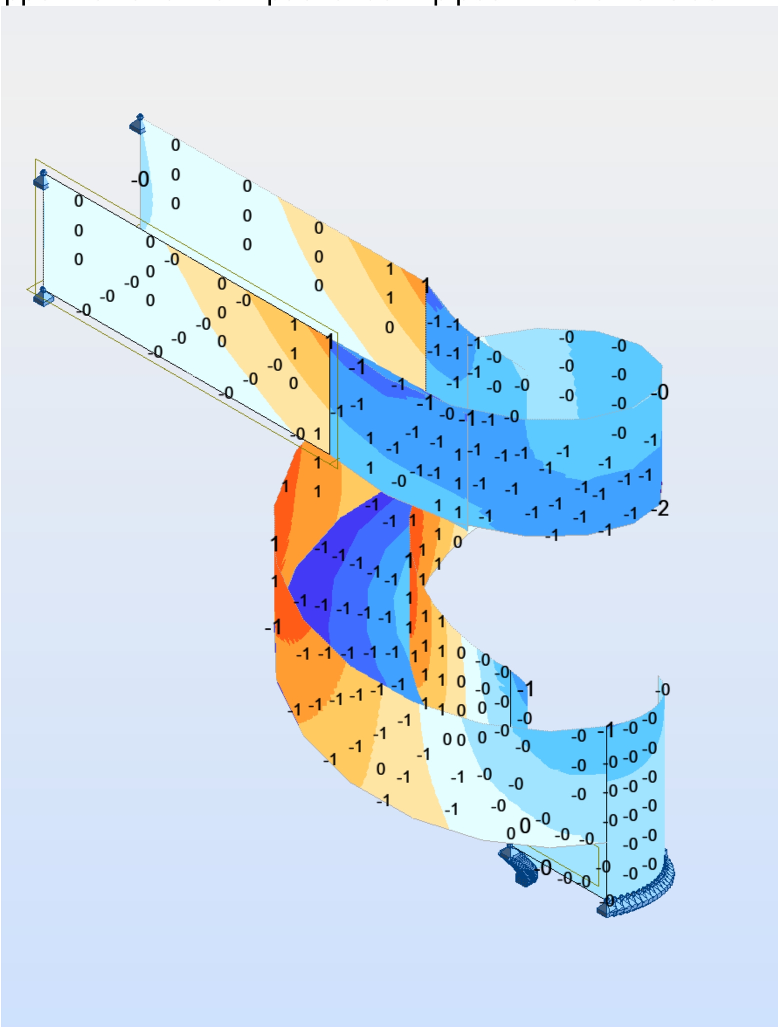

Figure 3 Scenario 1 - deformation in the vertical direction (pure pin)

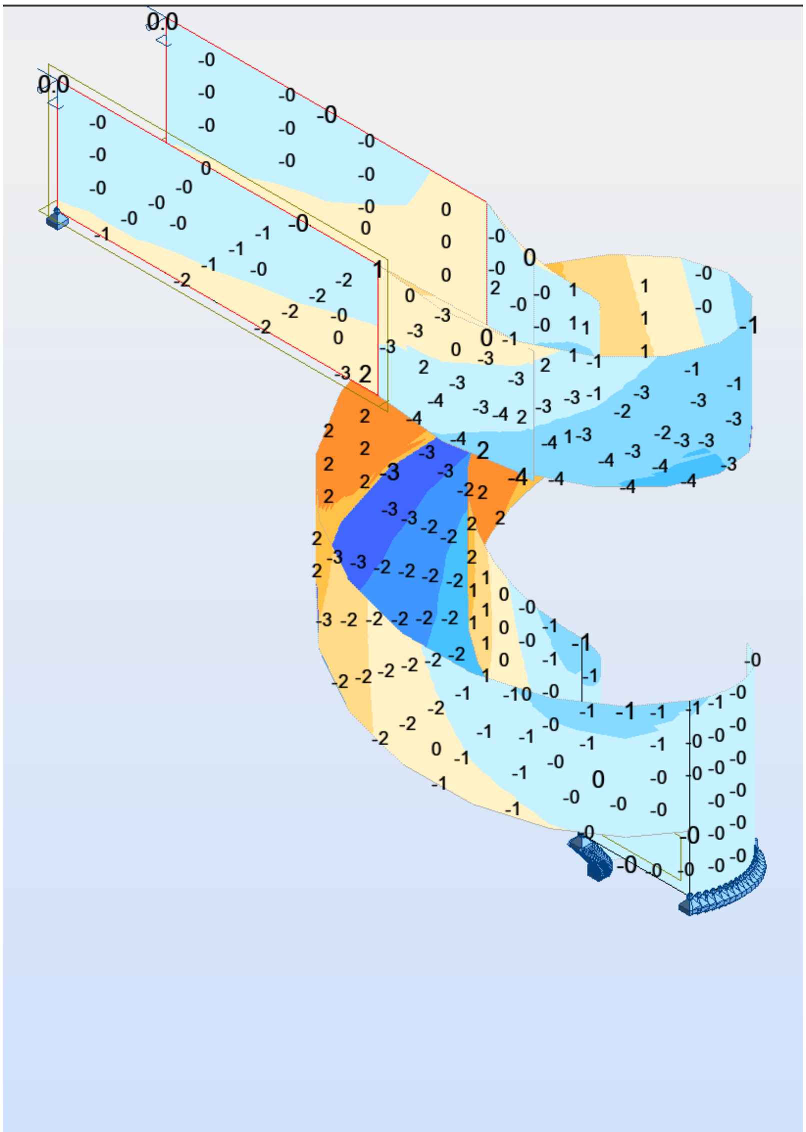

Figure 4 – Scenario 2 - deformation in the vertical direction spring (15kN/mm).

The second objective is more subjective and required the expertise of Bannan Construction. While the global deformation was understood using Robot and modelled with a high degree of confidence, the subjective components of crack control, concrete shrinkage, mix design and additives became an unquantifiable issue. The number of variables and their range meant that analysis was pointless. Management of these variables became the key. Where higher strength concretes provided greater strength, they also provided the most shrinkage. Where fibre may have offered a simpler reinforcing layout it came at the expense of effecting the rheology of the concrete (concrete flow) and therefore the quality of the finish. Nearly all positive solutions to improve the potential outcome also had a negative component. One option that seemed to have a large positive impact and no apparent downside was the use of a shrinkage reducing agent. In conjunction with the concrete supplier, Stevenson Concrete, we agreed to use Masterlife SRA 20 shrinkage reducing agent. This was adopted as the potential shrinkage was reduced by up to 50 percent.

CONSTRUCTION

In 2012 Bannan Construction was selected to build a large handcrafted almost entire in-situ concrete home in central Auckland which would eventually include over 1000m3 of concrete.

Figure 5 Physical scale model of the house constructed by Stevens Lawson.

Smooth Victorian architrave profiles enlarge by 200% where selected as the external finish for the concrete on both the home and the signature piece of the house which was the self-supporting Helical Staircase to the north of the home which gave access from the top deck to the external gardens.

Figure 6 Example of relief generated by timber profile

The construction would test both the knowledge and capability of Bannan Construction. Extensive research both locally and abroad was completed to examine how this stair could be completed in a single pour. It appeared that there were no local examples of pours this complex with such a high visual component. The international examples seemed to have some of the complexities but not all that this project demanded.

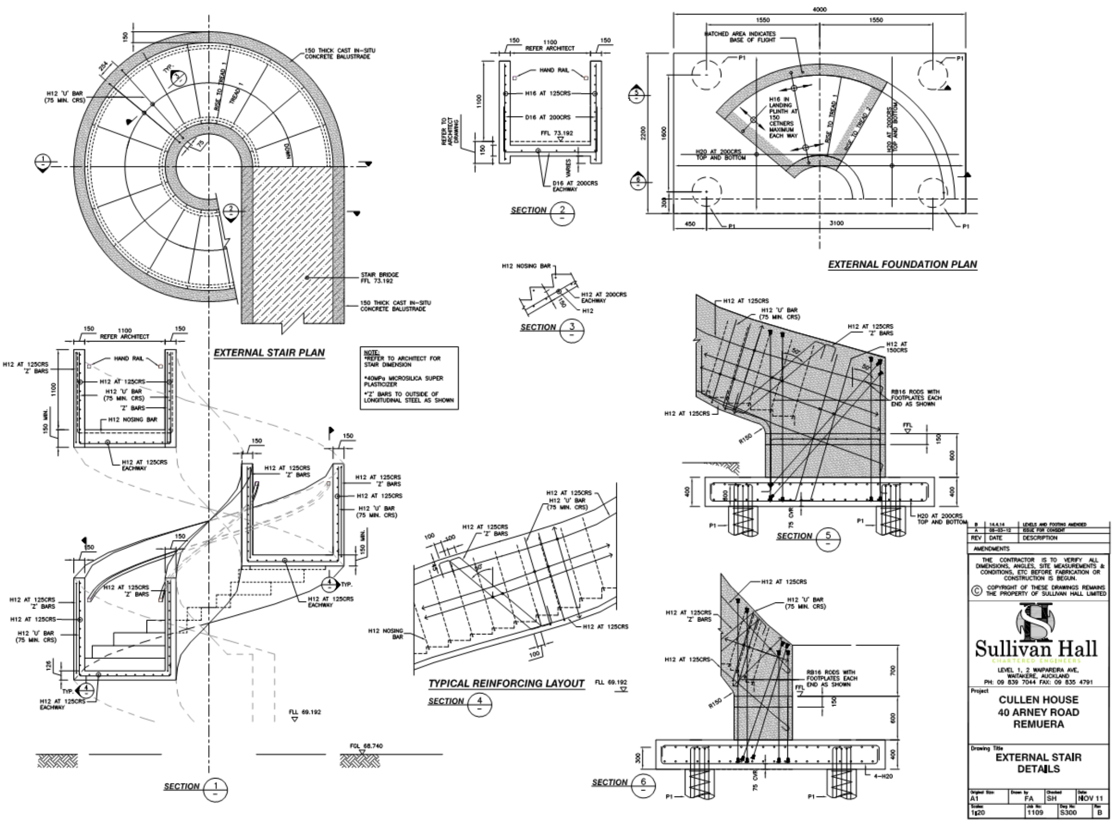

Figure 7 Engineering Design Plans

Bannan Construction worked closely with Sullivan Hall and the clients to describe how it was intended to be built. A number of practical recommendations were made including increasing the width of the rails from 100mm to 150mm as it was thought it too tight to contain the extensive reinforcing involved. In addition the treads of the stairs were tiled as it would be unable to avoid air pockets on the treads if they were left off the form as originally described. All were very supportive of my methods and permitted the changes.

Figure 8 – showing polystyrene core, timber form, pour staircase and protruding reinforcing for bridge

The piles and footing bed were constructed and accurately placed reinforcing protruding out to capture the helical base. Bannan Construction commenced with the mould form using formwork specifically purchased German manufactured bendable formwork to create the outer barrel.

Figure 9 Formwork set up on external barrel

Inside this barrel specialized computer cut poly wrapped in fibreglass were placed. To create these moulds Bannan Construction worked extensively with a major boat builder and their design team to develop all the tolerances and setbacks needed to encase the timber forms and finishes required.

Once the throat forms were fitted within the mould the external timber form liners were placed followed by the placement of the extensive reinforcing. This reinforcing was in fact one of the hardest construction components of the entire project. It had to be placed perfectly and held exactly in position during the build and the pour itself. As the reinforcing was placed it tensioned over the length of the helical which created various issues that needed solving prior to moving further. The steel was delivered to specific and varying radii and each piece spiralled into the form.

Figure 10 Picture of the Tread Moulds in staging area

The internal moulds were then placed which would form the internal side of the rails and the treads and risers. These forms came in small sections of four treads each. Before placement the wooden form liner was placed and then each one carried carefully in place and locked to the section in front by a specially designed system created by Bannan Construction. Placing these moulds in a confined space tested the construction team. Once in place, a scaffold and steps were erected to facilitate with both final adjustments of the forms and then the eventual pour.

The rail top capping had several pour hatches from the placement of the concrete so that Ross Bannan could work his way up from the base and then close off the hatches as the pour progressed.

Bannan Construction were also responsible for ensuring that the temporary formwork to create the concrete was capable of sustaining the weight and vibration of the concrete during the pour. The issue was exacerbated by the uneven helical loading that would occur. Bannan construction adopted an approach of identifying all the likely failure mechanisms that could develop with the formwork and then went about resolving each possible issue. Of particular concern to all parties was the extremely small tolerance for movement. The formwork had to remain true and consistent. The concrete used was a high slump mix (akin to self-compacting) from Stevenson's and created large loads by itself let which were amplified when externally vibrated. Self-compacting concrete was not used as it was decided that the density and colour change to the concrete would have been too distinguishable to the rest of the house. There were also doubts on the timeframe it would take to pour the stairs. Self-compacting mixes tend to cure quickly and it was felt that there was sufficient difficulties without time pressures from mix curing. To ensure that Ross Bannan knew what was happening during the pour there were several strategies implemented:

- Thin steel rings were placed around the form which were cut and then glassed together. If there was any widening of the barrel form these glassed areas would snap and identify the movement by the crack width in the glass.
- There were measure points up the exterior
- A 100mm deep layer of concrete was poured into the barrel at its base to stop any lateral base movement. This was later removed to expose the original footing base cap.
- Throughout the pour these measuring points were assigned to specific members of the team who relayed the information back to Ross Bannan during the pour.

For the pour itself Bannan Construction liaised directly with the concrete supplier Stevenson's to ensure they were aware of the significance of the pour. The traffic management team who were altering the footpaths in the area were notified so that they could ensure that the three trucks involved were not delayed. To ensure consistency of mix between trucks, Stevenson's sent a technician to maintain the high flow concrete and continuity of the trucks. Constant communication was relayed to the entire team to make sure that the pour never slowed or kept the mix flowing evenly throughout the mould. Despite the challenges of this project, the pour sequence was completed without a hitch. A testament to the planning by the build team, in particular to Bannan Construction.