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CONCRETE STRUCTURES USING FABRIC FORMWORK

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CONTENTS

SYNOPSIS

Using fabric formwork, it is possible to cast architecturally interesting, optimised structures that use up to 40% less concrete than an equivalent strength prismatic section, thereby offering the potential for significant embodied energy savings in new concrete structures. This paper reports on the philosophy of and background to fabric formwork before techniques for the design, optimisation and shape prediction of fabric formed concrete beams are presented.

The practicality of construction with non-orthogonal elements is discussed before the results of new structural test data, undertaken at the University of Bath on 4m span ‘T’ beam elements formed in reusable fabric moulds, are presented. Potential areas of future development for fabric formwork, including the use of woven advanced composite fabrics as permanent participating formwork and the feasibility of uniform strength prestressed beams, are then discussed.

1 INTRODUCTION

A prismatic concrete beam, with uniform transverse and longitudinal reinforcement percentages, has a constant moment and shear force capacity at every point along its length. In all but a few locations, such a member is by definition under utilised. The ubiquitous use of orthogonal moulds as formwork for such structures has resulted in a well-established vocabulary of prismatic forms for concrete structures, yet rigid formwork systems must resist considerable fluid pressures, may consume significant amounts of material and can be expensive to construct. Moreover, the resulting member requires more material and has a greater deadweight than one cast with a variable cross section.

Simple optimisation routines, described in this paper, may be undertaken to design a variable cross section member in which the flexural and transverse force capacity at any point on the element reflects the requirements of the loading envelope applied to it. The construction of structures with complex non-orthogonal geometries is often perceived to be both difficult and expensive, yet this paper demonstrates that by casting concrete into a flexible fabric membrane, architecturally interesting, optimised structures that reduce material use and take real advantage of the fluidity of concrete can be produced.

1.1 Fabric formwork

Fabric formwork has been used in offshore and geotechnical engineering since the early 1900s, but it was not until the 1960s that its widespread use began to grow, precipitated by the new availability of high strength, low cost fabrics[1]. Initial interest in the architectural possibilities of fabric formwork can be attributed to the Spanish architect Miguel Fisac, whose work in this field culminated in a patented method for the construction of prefabricated fabric formed wall panels[2].

Since then, multiple design and construction methods for fabric formwork have evolved. In Japan, Kenzo Unno's 'zero-waste' system for casting fabric formed walls[3] has been successful, while in North America significant savings in both material and labour costs have been recorded as a result of using fabric formwork in the construction of columns and footings[4]. Additional and ongoing research, led by Professor Mark West at the University of Manitoba's Centre for Architectural Structures and Technology (C.A.S.T), has further considered the architectural possibilities of fabric formwork for beams and trusses, in addition to its use for shells, panels, columns and walls, Figure 1.

Although it has a low embodied energy (of approximately 0.90MJ/kg)[6] concrete is used in vast quantities. In 2008 world production of cement amounted to approximately $2.8\text{x}10^9$ metric tons[7], with its manufacture estimated to account for some 3% of all global CO_2 emissions[8], providing further impetus for the design of optimised structures. Concrete volume savings in fabric formed beams, when compared to an equivalent strength prismatic member, of 40% have already been achieved[9, 10], illustrating the potential for fabric formwork to reduce the embodied energy of new building structures.

Yet fabric formwork does not simply facilitate reductions in material use. Forming concrete in a permeable mould allows air and water to escape from the formwork to provide a high quality surface finish that can be readily distinguished from an identical concrete cast against an impermeable mould, as illustrated in Figure 2. Reductions in *water:cement* ratio towards the external face of structures cast in permeable moulds have been widely reported[11] and provide a surface zone with improved hardness[12, 13] and reduced porosity[14]. The resulting concrete surface is more durable than one cast against impermeable formwork, with reductions in carbonation depth, chloride ingress and oxygenation reported in the literature[11].

For structures where the concrete grade specified is governed by durability rather than strength concerns, permeable formwork offers significant opportunities for embodied energy savings. For example, a C20 concrete mix cast in permeable formwork has been found to have a lower carbonation depth after 11 months than a C50 mix cast in conventional formwork[12], with such a reduction in concrete grade providing embodied energy savings of approximately 38%[6] – in addition to those savings already achieved simply by using fabric formwork to cast a structurally optimised form. Long term cost savings for concrete cast in permeable moulds have also been reported[15] and arise primarily from a reduction in maintenance and repair requirements.

Allowing water, but not cement, to drain from the surface zone is imperative when permeable formwork is used, and while Price[11] suggests a maximum pore size of 50μm be specified, much greater pore sizes have been successfully used by the authors.

The high quality surface finish of concrete cast in fabric further encourages the use of exposed internal concrete surfaces, the consequence of which is two-fold: extraneous wall and ceiling coverings can be omitted and the now exposed thermal mass may properly be used in the provision of thermal comfort.

2 DESIGN

2.1 Fabric

The critical aspect of fabric formwork for determining shape and therefore aesthetic is the fabric itself. Although almost any woven fabric can be used as formwork for fabric cast concrete, tensile strengths in both warp and weft directions must be sufficient to hold the wet concrete and a low creep modulus is desirable to limit formwork deformations during casting and curing. The available literature illustrates the use of a range of fabrics as formwork, including hessian[9] and geotextiles[16], while more recent experimental work undertaken at the University of Bath has used a woven polyester fabric that has previously been utilised in the construction of underwater concrete structures.

Once a suitable fabric has been chosen, a number of methods are available to determine the final shape of the fluid filled flexible membrane. Schmitz[17] used an iterative finite element based procedure to determine the form of fabric formed wall panels, while Veenendaal[18] implemented dynamic relaxation to predict the final shape of fabric formed beams. Empirical relationships determined by Bailiss[9] provide a less rigorous solution to the same problem, but have nevertheless been used successfully[10], while Foster[19] used a simple step-wise based method to iteratively determine the shape of the concrete filled fabric. The complete solution, which requires the use of incomplete elliptic integrals, is given separately by Iosilevskii[20].

2.2 Reinforcement

The reinforcement of variable section members adds some complexity to the construction process, yet fundamentally does not differ from an orthogonal structure. The provision of end anchorage has been seen in previous work[10] to be a crucial consideration and both externally welded steel plates (Figure 3) and transversely welded internal bars have been used to achieve this.

The provision of transverse reinforcement in a variable section member simply requires a varying link size, which is easily achieved but can add cost to the construction process. It is therefore imperative that any reinforcement specified be used to its full capacity.

2.3 Analysis

Structural design procedures for bending moment shaped beams, as developed at the University of Bath[9, 10], are based on a sectional approach that aims to satisfy the bending and shear requirements of the beam at every point along its length. Where open web beam sections are desired (as discussed later), additional consideration must be given to the effects of Vierendeel action in the member (detailed elsewhere[21]).

Flexural strength calculations are undertaken by first dividing the element into a number of equally spaced sections. By assuming that the longitudinal steel has yielded, the lever arm distance required to provide the required moment capacity at each section is quickly determined by equilibrium, Eq.(1) and Figure 4. This is repeated at each section along the length of the member to determine the optimised reinforcement layout for a given loading envelope.

$$z = \frac{M_{Rd}}{F_{b,H}} \qquad \text{Eq.(1)}$$

Where z is the lever arm, M is the applied moment and $F_{b,H}$ the horizontal component of tension force on the section.

For a beam with just one layer of reinforcement, the resulting effective depth is then proportional to the bending moment on the section. In such a situation, the vertical component of force in the bar will be equal to the applied shear force according to Eq.(2). This suggests that the inclined longitudinal bar may be used to provide both flexural and shear force capacity to the section.

$$V = \frac{dM}{dx} = F_{b,v} \qquad \text{Eq.(2)}$$

Where V is the shear force, M is the applied moment, x is the position along the beam.

However, utilising a longitudinal bar to provide vertical force capacity close to the supports in a simply supported beam requires the bar to be fully anchored at its ends. The use of external steel plates to provide such anchorage is an unsatisfactory solution as it introduces the potential for brittle failure, exposes the internal reinforcement to corrosion and increases construction complexity.

Furthermore, for a structure subject to an envelope of loads the longitudinal reinforcement position will be determined by the maximum moment on each section. Where a structure is subject to both point and uniformly distributed loads, it is feasible that the maximum moment and maximum shear forces on a section will not originate from the same load case. In such a situation, a bar placed for moment capacity will then be incorrectly inclined to provide the desired vertical force, and thus transverse reinforcement will be required. However, an inclined bar still provides some value of vertical force, which in design may be added to the shear resistance of the section to reduce its transverse reinforcement requirements (c.f. BS EN 1992-1-1[22] (cl.6.2.1)).

The assessment of shear capacity in fabric formed beams has previously been undertaken to BS 8110-1[23], yet the empirical 'concrete contribution' of this method is not necessarily applicable to the design of variable section beams. This assertion is supported by the available test data[9, 10], where shear has been seen to be the predominant failure mode.

The variable angle truss model, as adopted by BS EN 1992-1-1[22] for sections with transverse reinforcement, considers only the capacity provided to the member by the reinforcement and thus avoids a reliance on empirical relationships to determine shear strength. A yet more attractive approach is found in compression field theory[24], which allows the detailed analysis of any cross section shape to be undertaken. However, this approach is yet to be taken up by European code writing committees.

3 CONSTRUCTION

Fabric formwork provides a fundamentally simple construction method and an optimised beam can be formed using only a sheet of fabric and modest supporting frame, as illustrated in Figure 5. The fabric, as discussed above, is completely reusable, either for a repeat element or in an entirely new beam geometry.

More stringent construction control is achieved through the use of the 'keel mould' for the production of pre-cast beams, Figure 6. Here, the fabric is held vertically and secured to a 'keel' that has been pre-cut to the desired longitudinal beam profile. The fabric is then prestressed in two directions before being fixed in position. Prestressing the fabric prevents wrinkling during construction and minimises the volume of concrete in the tension zone.

The 'pinch mould' (Figure 7) may alternatively be used to create pre-cast beams and trusses with more complex geometries. Using 'pinch points' the sheets of fabric can be held together during casting, creating an opening in the resulting element. This is a potentially important consideration for the provision of building services, but requires more careful analysis in design, as discussed above.

3.1 Building services

The aesthetic appeal of variable section members, coupled with a high quality surface finish and the additional advantages of exposed thermal mass make fabric formwork an ideal means by which architectural, structural and building service requirements can be integrated.

Using the 'pinch mould' construction method, pre-cast variable section fabric formed beams can easily be created with voids in their midspan zones, Figure 8. Such sections are rarely used in conventional reinforced concrete design, yet provide a simple method for the routing of service ductwork. However, such an arrangement may detract from the aesthetic appeal of exposed, fabric formed soffits and the provision of services through a raised floor may be more appropriate (Figure 9). Such an approach holds additional advantages for the circulation of air exposed to the concrete slab and allows the building to be easily adapted for future changes in use.

3.2 Costs

Whilst cost savings have been recorded in projects that made use of fabric formwork for the construction of columns and footings[4], there is limited data available for the construction of more complex variable section elements. However, Pallet[15] suggests that labour cost savings may be achieved as formwork stripping and work cycle times are improved when concrete is cast in fabric. Coupled with the aforementioned material use reductions, the economic advantage of fabric formwork is increasingly apparent.

The construction of complex doubly curved concrete elements remains entirely feasible using well established computed numerically controlled (CNC) manufacturing processes to produce steel moulds for use as formwork. However, such an approach is both expensive and time consuming, and is suitable only where multiple identical elements are desired. Using fabric formwork, the creation of multiple 'one-offs' from a single sheet of fabric is entirely feasible, and can be undertaken anywhere in the world using simple construction techniques.

4 CONSTRUCTION EXAMPLES

Whilst fabric formwork is increasingly used in North America in the construction of concrete columns and footings, there are far fewer examples of beam and slab construction. D'Aponte *et al.*[25] provide details of a number of small houses built using fabric formwork, and construction techniques for such structures are being refined in ongoing work at the Yestermorrow Design School, Vermont[26].

4.1 T-Beams

Using the sectional analysis method described above, four 8m span fabric formed beams were recently designed at the University of Bath for use as a precast elements in reinforced concrete frame construction. These four elements were then scaled by 50% to facilitate structural testing, as described below.

The beams were designed to the envelope of loads summarised in Figure 10, with additional dead load being applied to account for the cubic loss in concrete volume that occurs when elements are scaled linearly (all load partial safety factors are set to 1.00). The beams were tested in nine-point bending, with the point loads required to achieve the design moment envelope given in Figure 11 (where a self-weight of *2.7kN/m* is assumed).

The four beams had identical external dimensions and varied only in the arrangement of their transverse and longitudinal reinforcement, as illustrated in Figure 12. Beams 1 and 2 were designed without considering the inclination of the longitudinal tensile steel, while Beams 3 and 4 considered the longitudinal steel to provide shear capacity at the supports. Beams 1 and 3 were transversely reinforced with minimum links according to BS EN 1992-1-1[22] while Beams 2 and 4 were provided with links only where required according to an analysis using the modified compression field theory (c.f. Collins *et al.*[24]). A concrete strength of 40MPa and steel yield strength of 500MPa was assumed for design purposes, with the actual concrete strengths and steel yield strengths at the time of testing being given in Table 1 and Table 2 respectively.

Construction of the beams was undertaken using the keel mould, as described above and illustrated in Figure 13. A flat face at the supports was formed using a simple steel plate, pushed into the tensioned fabric and screwed to the plywood keel. The transverse and longitudinal steel reinforcement was bent and cut to the required shape before being tied together and placed into the mould, and a minimum cover to the longitudinal steel of 20mm was achieved using plastic spacers. The vertical sides of the top slab were cast against phenolic plywood that had first been treated with a release agent. The fabric was not treated in any way and all casts were made in the same mould using the same fabric, which was simply brushed down after use.

Compared to an equivalent orthogonal section, and excluding the top slab, the optimised beam profile provides a concrete material saving of approximately 35%.

The beams were demoulded three days after casting and allowed to cure for at least 20 days prior to testing. Beam 1 is shown in Figure 14, where the disparity in concrete quality between that cast against plywood and that cast in fabric is again apparent.

The beams were tested in the loading frame shown in Figure 15 to simulate the application of a uniformly distributed load, with the loads required to achieve the design moment envelope given in previously in Figure 11. The beams were all tested in load control, with a constant ratio of P_1:P_2 of *1:2.44* applied up to the maximum load. The load-displacement response of each beam is summarised in Figure 16 and apposite test results are given in Table 1. The design failure load of 107kN was marginally exceeded in all tests, with these relatively small increases accounted for by the actual yield stress of the bars being higher than that assumed for design (Table 2) and the potential for small errors in the position of the longitudinal bars. In general the sectional method provides an accurate technique for determining the moment capacity of the variable section element.

Beam 1 reached a maximum load of 114kN and after displaying some ductility the cantilever loads P_1 were removed. Beam 1 was then loaded by the five central point loads at a constant load of approximately 86kN up to a midspan deflection of 85mm. Subsequently, load was applied at the mid-span only, with a constant load of 54kN carried by the section up to its maximum displacement of 90mm, as shown in Figure 16.

Beams 2, 3 and 4 were tested in a similar manner, but after achieving ductility at their maximum load capacities (Figure 16) were loaded by the central point load only. Beam 4 achieved a slightly higher maximum load than the first three tests, but this increase is not considered to be significant.

All beams displayed a ductile response, with yielding of the longitudinal steel leading eventually to compression failures in the top slab. Cracking of the sections was well distributed (Figure 17) and no shear failures were recorded, in contrast to tests previously undertaken at the University of Bath[9, 10] in which shear was the predominant failure mode.

The four beams described above displayed similar load-deflection responses, with almost identical cracked and uncracked stiffnesses recorded. This demonstrates that the two shear design methods have relatively little effect on the overall member response, and the sectional design approach may thus be used with confidence in the design of optimised beam structures. In addition, the keel mould has now been successfully demonstrated as a feasible construction method for fabric formed concrete structures.

The similar load capacities recorded between Beams 1-4 further suggests that transverse reinforcement design may be satisfactorily undertaken using either BS EN 1992-1-1[22] or the modified compression field theory. Whilst the beams described above were designed to fail in flexure, future work will be required to comprehensively assess the shear behaviour of variable section members. This will then allow more detailed design guidance to be provided.

Test	Concrete strength at test (N/mm^2)	Maximum load, $2P_1 + 5P_2$, (kN)	Midspan deflection at final load (mm)	Failure mode
Beam 1	42	114	89	Flexure
Beam 2	39	119	86	Flexure
Beam 3	44	115	89	Flexure
Beam 4	33	133	89	Flexure

Table 1 *— Test result summary, Beams 1-4*

	3mm bar
0.2% proof stress	630MPa

	10mm bar	12mm bar
Yield stress	566MPa	576MPa

Table 2 *— Measured steel properties at test.*

4.2 Serviceability

The advantage of a prismatic beam is its constant stiffness prior to cracking. The variable section beam is inherently more flexible than its prismatic counterpart and thus the serviceability limit state may become a concern. For example, in the beams described above, applying a deflection limit of *span/250* reduces the permissible load capacity by around 30%, as highlighted in Figure 16.

Yet stringent deflection requirements can do little except add deadweight. Designing a structure to follow the loads applied to it, without adding unnecessary material is a more sensible - moreover, sustainable – approach to structural design. For those situations where stringent deflection criteria are truly important, the use of prestressed reinforcement provides an ideal solution. With fabric formwork, uniform strength prestressed beams (as described by Guyon[27], where the extreme fibres at every point on the beam are at their compressive or tensile stress limit, Figure 18) are entirely feasible and display excellent behaviour at the serviceability limit state.

With fabric formwork, optimised, materially efficient, aesthetically pleasing structures that minimise embodied energy and encourage the appropriate use of thermal mass are possible. The construction of such structures can now be undertaken using a simple, reusable formwork system.

5 THE FUTURE

The provision of reinforcement to a continually varying cross section has the potential to add significantly to construction time. A participating fabric system in which a composite fabric incorporating carbon fibres acts as both formwork and reinforcement may therefore be advantageous in some situations. Improvements in three-dimensional weaving capabilities may allow designers to specify carbon fibre weave directions and densities at various points along the length of a beam based on the applied loads. The resulting formwork could then simply be filled with concrete to provide an optimised, composite reinforced structure that minimises material use.

There are, however, a number of technical hurdles to clear before such a method could be used in general construction. In addition to vandalism and fire protection, an adequate bond between concrete and reinforcement must be provided for the life of the structure and the existing architectural merit of fabric formed concrete structures must be maintained.

Flexural elements are fundamentally inefficient and it is in the design of shell structures that real material savings may be found. Using a combination of inexpensive fabric as formwork and lightweight, durable, high strength carbon fibre sheets as reinforcement, medium span shell elements such as those already produced at CAST may become a realistic alternative to existing floor and roof systems, as illustrated in Figure 18.

6 CONCLUSIONS

The design of fabric formed concrete structures has, to date, been led primarily by architectural concerns. Work to provide more complete design guidance for these remarkable structures is now well underway. Fabric formed concrete beams offer significant advantages for designers, including reductions in material use, ease of construction and aesthetic appeal. Further advantages may be gained through the use of prestressed reinforcement, either steel or fibre reinforced polymers, where improvements in both serviceability and ultimate limit state behaviour can be obtained. Additional work is required to investigate the use of flexible fibre reinforced polymer fabrics and grids as both external participating reinforcement in beam structures and as internal reinforcement in thin-shell elements.

By designing optimised concrete structures, significant savings in material use can be achieved, with concomitant reductions in both embodied carbon and construction cost. Fabric formwork not only provides a simple means by which such structures can be cast, but by allowing excess pore water to bleed from the surface of the concrete the resulting element is both durable and beautiful. Fabric formwork thus offers exciting opportunities for engineers and architects in the move towards a more sustainable construction industry.

6.1 Acknowledgements

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Figure 1 - Research undertaken at C.A.S.T.

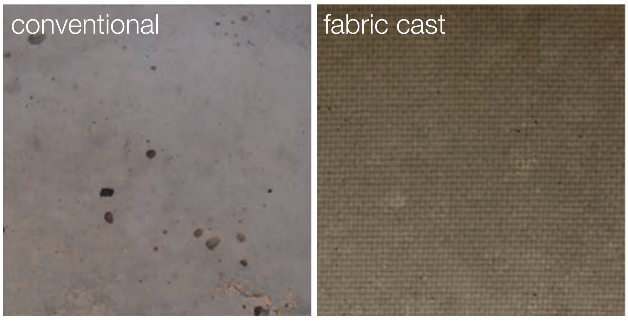

Figure 2 - Identical concrete cast in impermeable (l) and permeable (r) moulds

a) Hooked end plate

b) Longitudinal bar welded to end plate

c) Example beam with visible end plates

Figure 3 - Anchorage using welded end plates

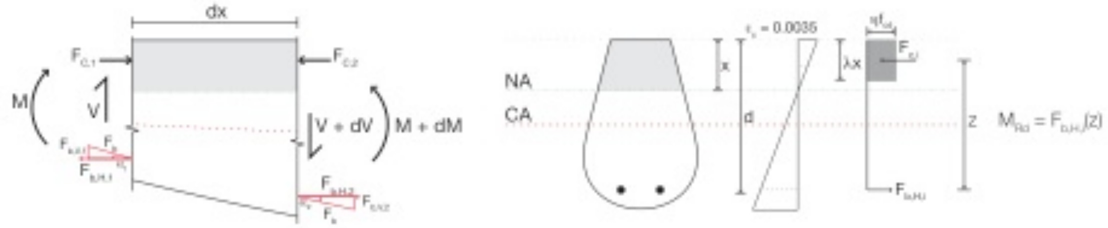

Figure 4 - Steel reinforced section flexural design basis

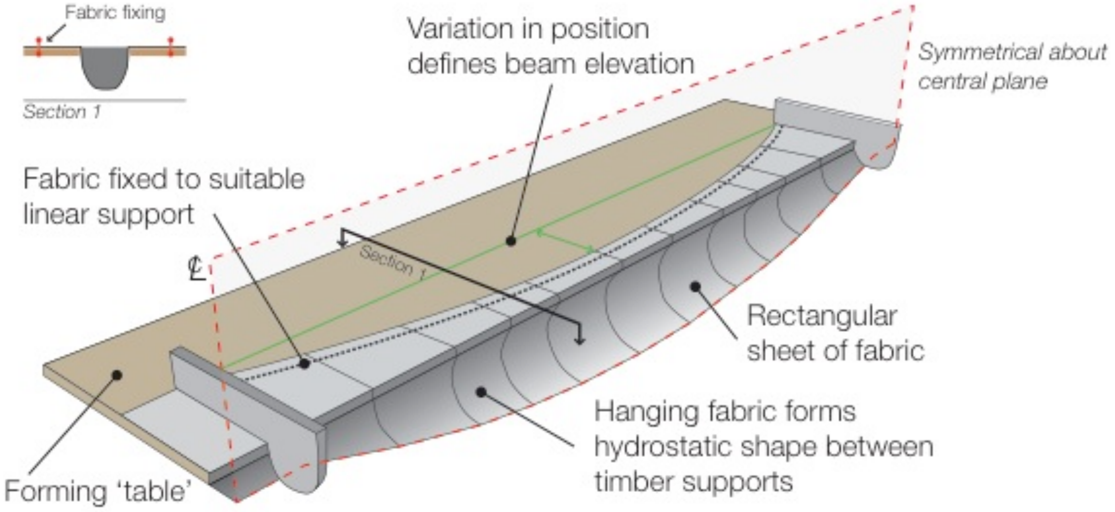

Figure 5 - Construction using fabric

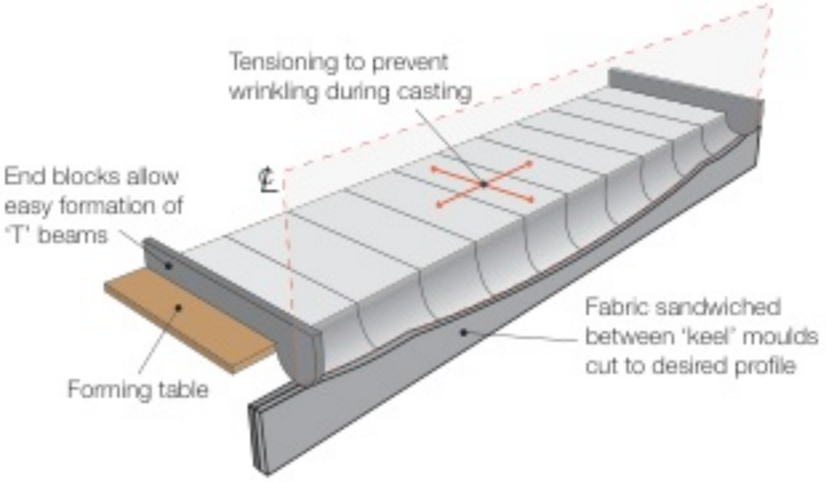

Figure 6 - Construction using the keel mould

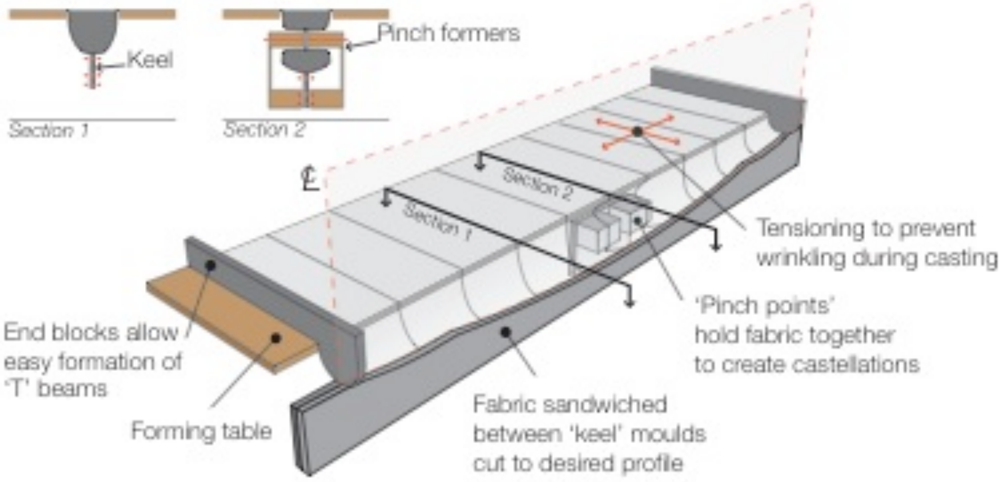

Figure 7 - Construction using the pinch mould

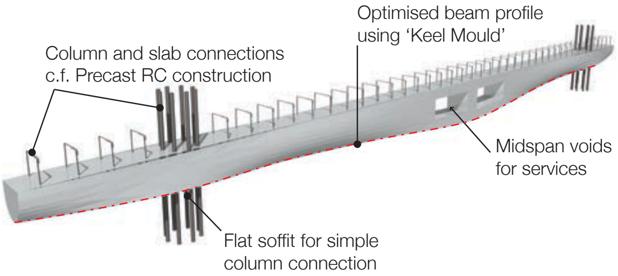

Figure 8 - Pre-cast beam element

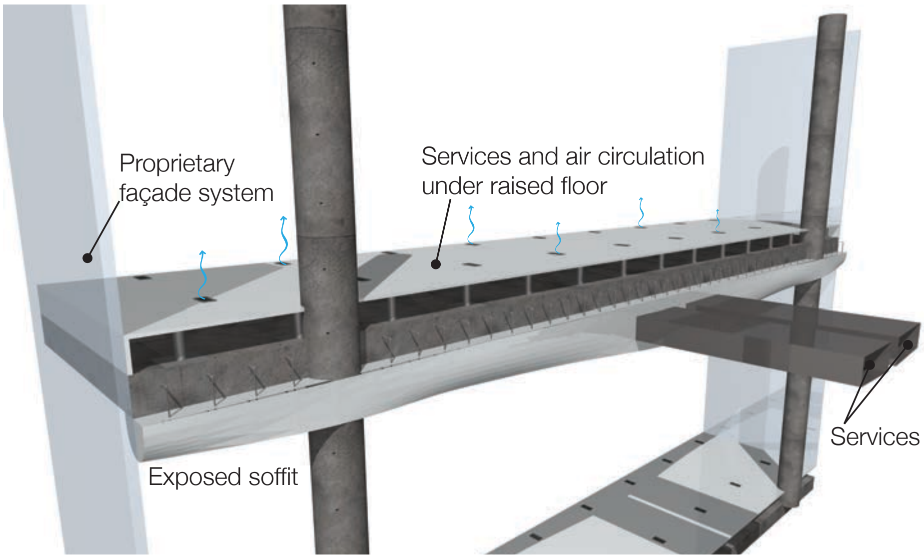

Figure 9 - Integration of building services

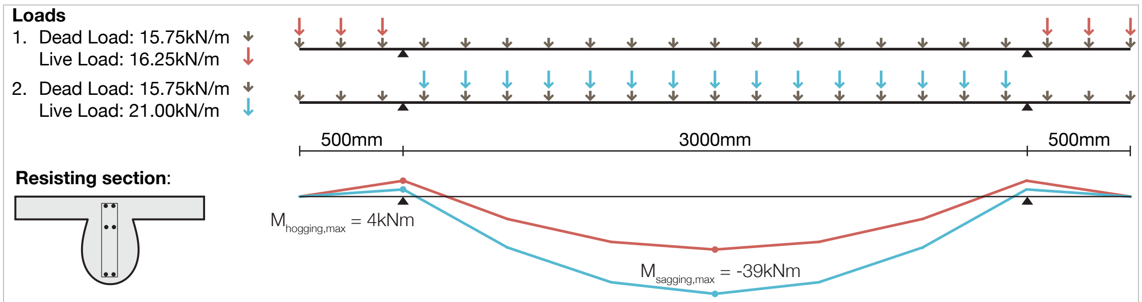

Figure 10 - Load cases and resulting shear and moment envelopes

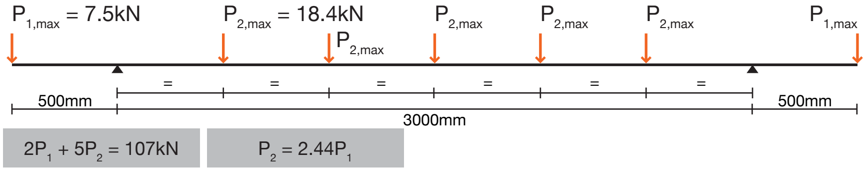

Figure 11 - Test loads

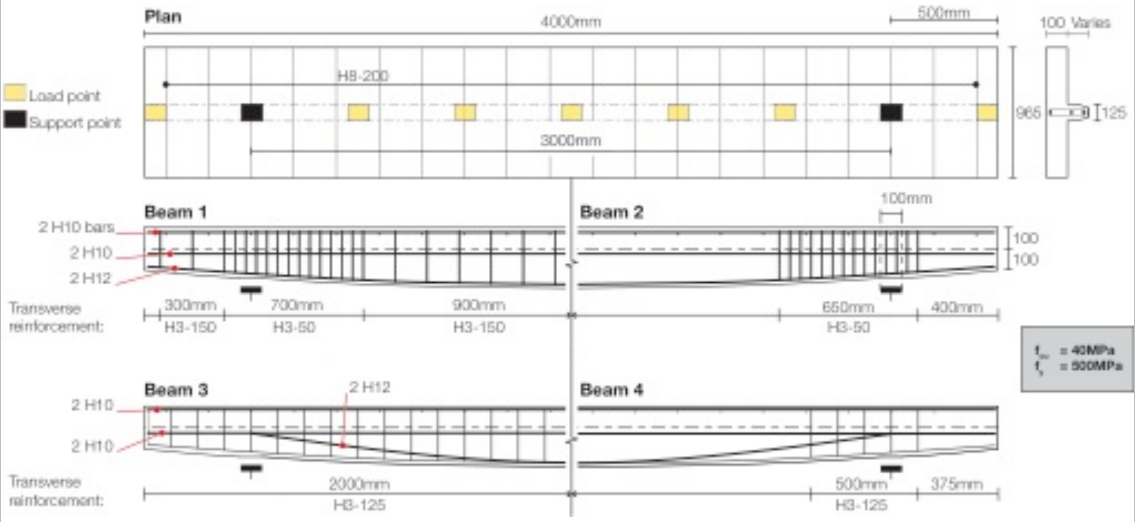

Figure 12 - T-Beam general arrangement

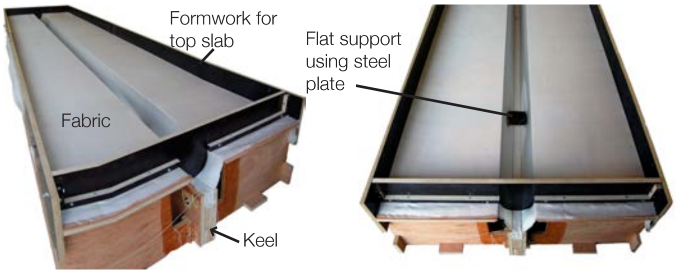

Figure 13 - Keel mould table

Figure 14 - T-Beam formed in fabric

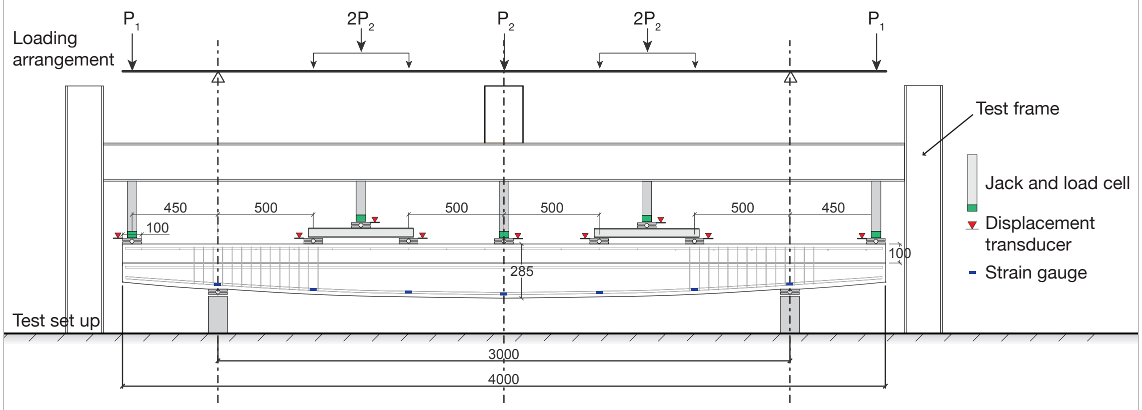

Figure 15 - Test set up

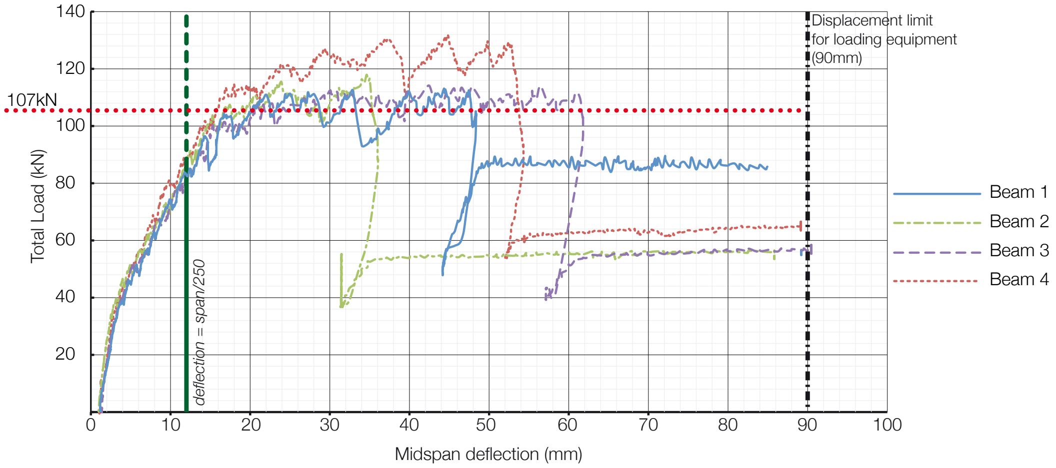

Figure 16 - Load-Displacement test results, Beams 1-4

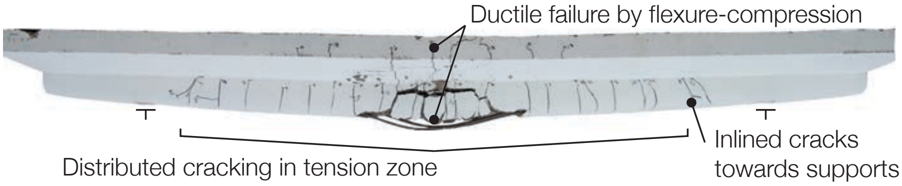

Figure 17 - Typical failure mode

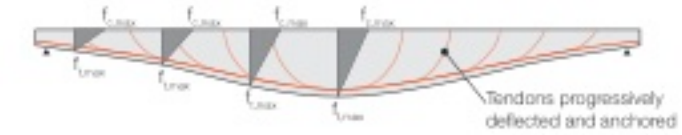

Figure 18 - Uniform strength prestressed beams

Figure 19 - Fabric cast columns supporting fabric formed shells (image courtesy CAST)