

CONCRETE STRUCTURES USING FABRIC FORMWORK

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SYNOPSIS

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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.

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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 fabrics¹. 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 panels².

Since then, multiple design and construction methods for fabric formwork have evolved. In Japan, Kenzo Unno's 'zero-waste' system for casting fabric formed walls³ 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 footings⁴. 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 2.8×10^9 metric tons⁷, with its manufacture estimated to account for some 3% of all global CO₂ emissions⁸, 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 reported¹¹ and provide a surface zone with improved hardness^{12, 13} and reduced porosity¹⁴. 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 literature¹¹.

82 For structures where the concrete grade specified is governed by durability rather than strength
83 concerns, permeable formwork offers significant opportunities for embodied energy savings. For
84 example, a C20 concrete mix cast in permeable formwork has been found to have a lower carbonation
85 depth after 11 months than a C50 mix cast in conventional formwork¹², with such a reduction in concrete
86 grade providing embodied energy savings of approximately 38%⁶ – in addition to those savings already
87 achieved simply by using fabric formwork to cast a structurally optimised form. Long term cost savings
88 for concrete cast in permeable moulds have also been reported¹⁵ and arise primarily from a reduction in
89 maintenance and repair requirements.

90 Allowing water, but not cement, to drain from the surface zone is imperative when permeable
91 formwork is used, and while Price¹¹ suggests a maximum pore size of 50 μ m be specified, much greater
92 pore sizes have been successfully used by the authors.

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

96 **2 DESIGN**

97 **2.1 Fabric**

98 The critical aspect of fabric formwork for determining shape and therefore aesthetic is the fabric itself.
99 Although almost any woven fabric can be used as formwork for fabric cast concrete, tensile strengths in
100 both warp and weft directions must be sufficient to hold the wet concrete and a low creep modulus is
101 desirable to limit formwork deformations during casting and curing. The available literature illustrates
102 the use of a range of fabrics as formwork, including hessian⁹ and geotextiles¹⁶, while more recent
103 experimental work undertaken at the University of Bath has used a woven polyester fabric that has
104 previously been utilised in the construction of underwater concrete structures.

105 Once a suitable fabric has been chosen, a number of methods are available to determine the final shape
106 of the fluid filled flexible membrane. Schmitz¹⁷ used an iterative finite element based procedure to
107 determine the form of fabric formed wall panels, while Veenendaal¹⁸ implemented dynamic relaxation to
108 predict the final shape of fabric formed beams. Empirical relationships determined by Bailiss⁹ provide a
109 less rigorous solution to the same problem, but have nevertheless been used successfully¹⁰, while Foster¹⁹
110 used a simple step-wise based method to iteratively determine the shape of the concrete filled fabric. The
111 complete solution, which requires the use of incomplete elliptic integrals, is given separately by
112 Iosilevskii²⁰.

113 **2.2 Reinforcement**

114 The reinforcement of variable section members adds some complexity to the construction process, yet
115 fundamentally does not differ from an orthogonal structure. The provision of end anchorage has been
116 seen in previous work¹⁰ to be a crucial consideration and both externally welded steel plates (Figure 3)
117 and transversely welded internal bars have been used to achieve this.

118 The provision of transverse reinforcement in a variable section member simply requires a varying link
119 size, which is easily achieved but can add cost to the construction process. It is therefore imperative that
120 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 elsewhere²¹).

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.

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

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.

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

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 1992-1-1²² (cl.6.2.1)).

The assessment of shear capacity in fabric formed beams has previously been undertaken to BS 8110-1²³, 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 1992-1-1²² 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

155 in compression field theory²⁴, which allows the detailed analysis of any cross section shape to be
156 undertaken. However, this approach is yet to be taken up by European code writing committees.

157 **3 CONSTRUCTION**

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

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

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

170 **3.1 Building services**

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

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

181 **3.2 Costs**

182 Whilst cost savings have been recorded in projects that made use of fabric formwork for the
183 construction of columns and footings⁴, there is limited data available for the construction of more
184 complex variable section elements. However, Pallet¹⁵ suggests that labour cost savings may be achieved
185 as formwork stripping and work cycle times are improved when concrete is cast in fabric. Coupled with
186 the aforementioned material use reductions, the economic advantage of fabric formwork is increasingly
187 apparent.

188 The construction of complex doubly curved concrete elements remains entirely feasible using well
189 established computed numerically controlled (CNC) manufacturing processes to produce steel moulds for
190 use as formwork. However, such an approach is both expensive and time consuming, and is suitable only
191 where multiple identical elements are desired. Using fabric formwork, the creation of multiple ‘one-offs’
192 from a single sheet of fabric is entirely feasible, and can be undertaken anywhere in the world using
193 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, Vermont²⁶.

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 1992-1-1²² 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

235 exceeded in all tests, with these relatively small increases accounted for by the actual yield stress of the
 236 bars being higher than that assumed for design (Table 2) and the potential for small errors in the position
 237 of the longitudinal bars. In general the sectional method provides an accurate technique for determining
 238 the moment capacity of the variable section element.

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

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

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

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

256 The similar load capacities recorded between Beams 1-4 further suggests that transverse reinforcement
 257 design may be satisfactorily undertaken using either BS EN 1992-1-1²² or the modified compression field
 258 theory. Whilst the beams described above were designed to fail in flexure, future work will be required to
 259 comprehensively assess the shear behaviour of variable section members. This will then allow more
 260 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

261 **Table 1** – Test result summary, Beams 1-4

	3mm bar	10mm bar	12mm bar
0.2% proof stress	630MPa	566MPa	576MPa

262 **Table 2** – Measured steel properties at test.

263

264 4.2 Serviceability

265 The advantage of a prismatic beam is its constant stiffness prior to cracking. The variable section beam

266 is inherently more flexible than its prismatic counterpart and thus the serviceability limit state may
267 become a concern. For example, in the beams described above, applying a deflection limit of $span/250$
268 reduces the permissible load capacity by around 30%, as highlighted in Figure 16.

269 Yet stringent deflection requirements can do little except add deadweight. Designing a structure to
270 follow the loads applied to it, without adding unnecessary material is a more sensible - moreover,
271 sustainable – approach to structural design. For those situations where stringent deflection criteria are
272 truly important, the use of prestressed reinforcement provides an ideal solution. With fabric formwork,
273 uniform strength prestressed beams (as described by Guyon²⁷, where the extreme fibres at every point on
274 the beam are at their compressive or tensile stress limit, Figure 18) are entirely feasible and display
275 excellent behaviour at the serviceability limit state.

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

279 **5 THE FUTURE**

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

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

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

296 **6 CONCLUSIONS**

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

305 By designing optimised concrete structures, significant savings in material use can be achieved, with
306 concomitant reductions in both embodied carbon and construction cost. Fabric formwork not only
307 provides a simple means by which such structures can be cast, but by allowing excess pore water to bleed

308 from the surface of the concrete the resulting element is both durable and beautiful. Fabric formwork
309 thus offers exciting opportunities for engineers and architects in the move towards a more sustainable
310 construction industry.

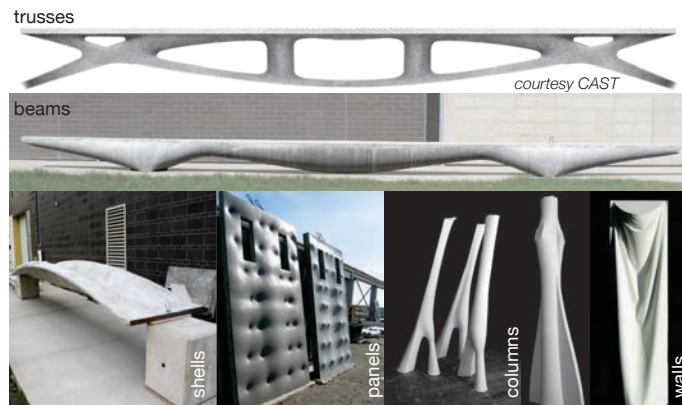
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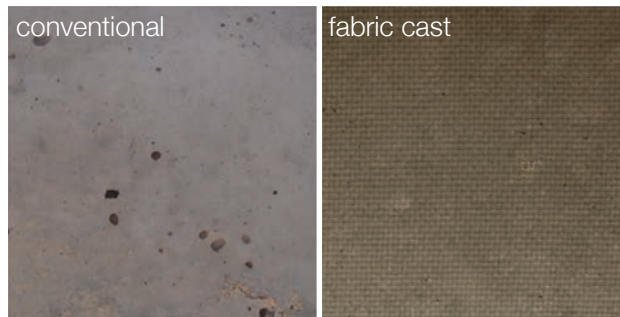
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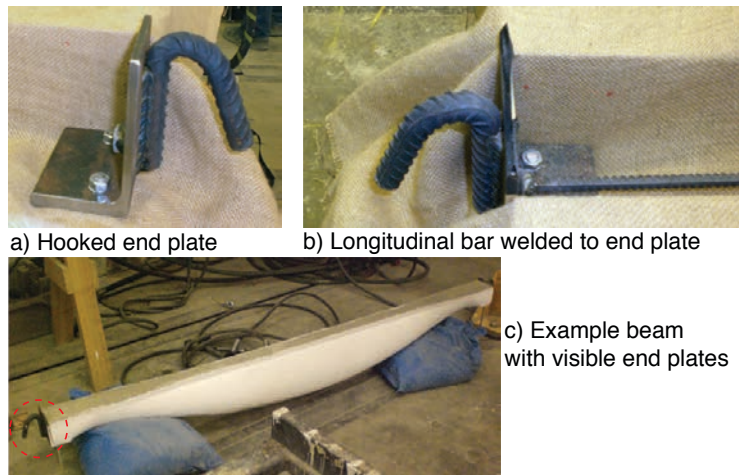
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Figure 1 - Research undertaken at C.A.S.T.



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



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Figure 3 - Anchorage using welded end plates

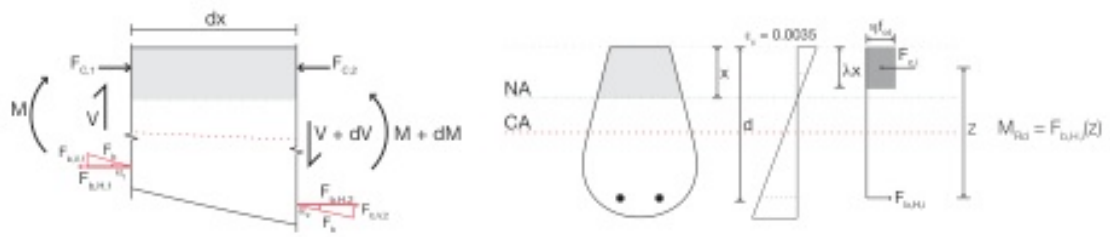


Figure 4 - Steel reinforced section flexural design basis

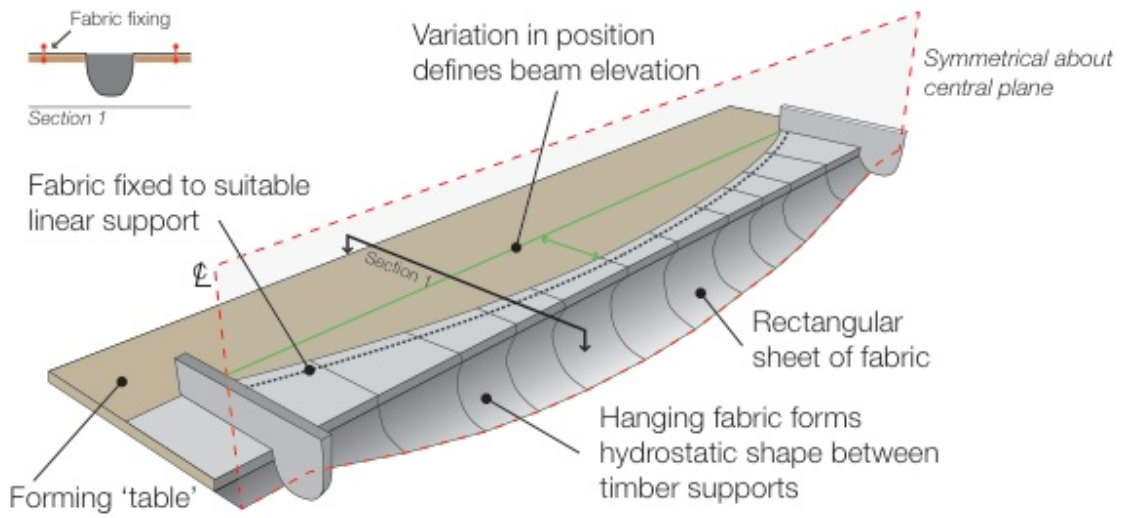


Figure 5 - Construction using fabric

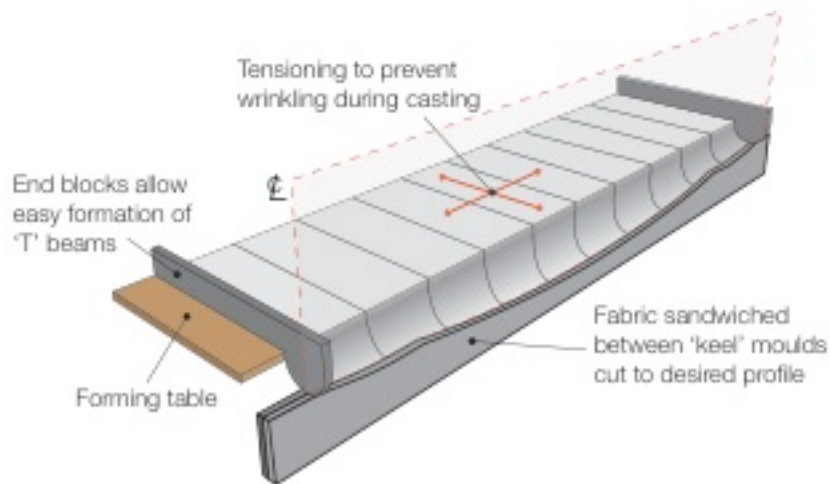


Figure 6 - Construction using the keel mould

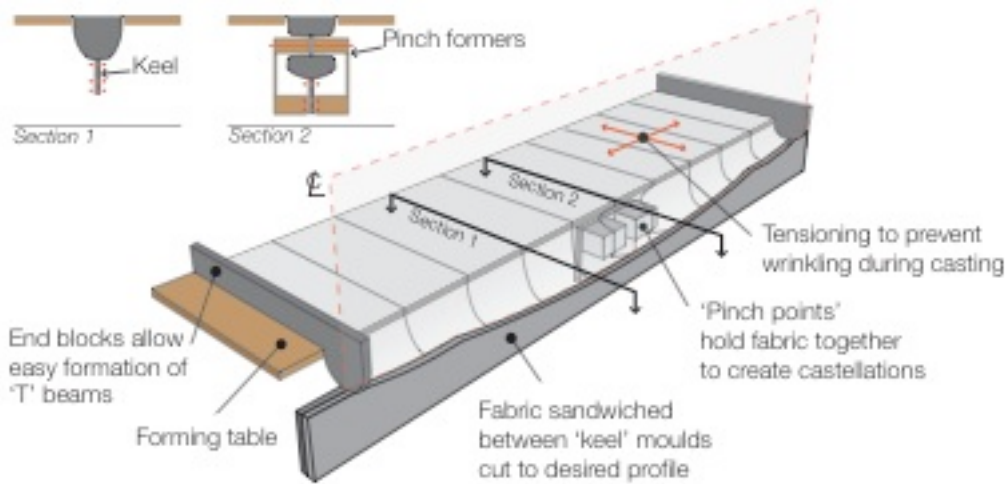


Figure 7 - Construction using the pinch mould

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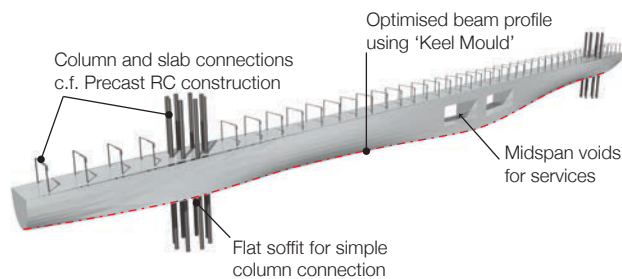


Figure 8 - Pre-cast beam element

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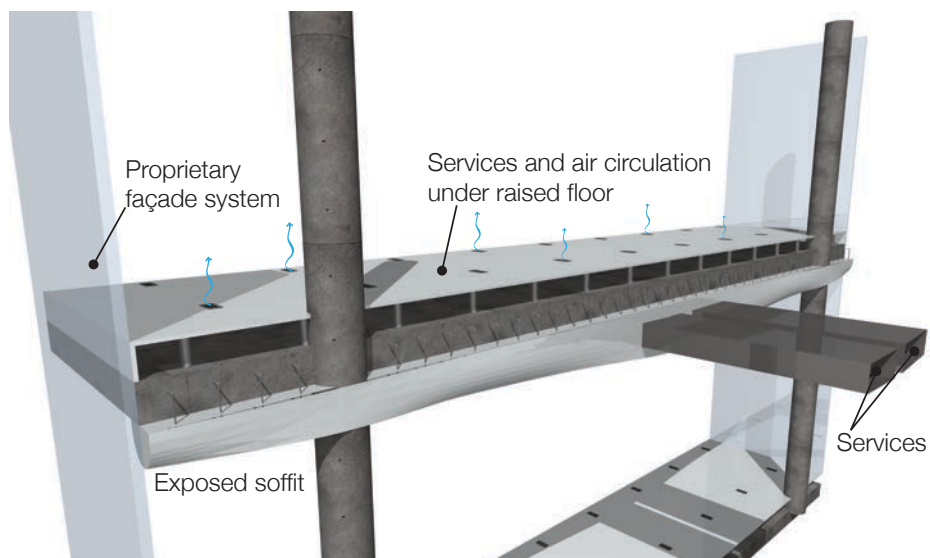


Figure 9 - Integration of building services

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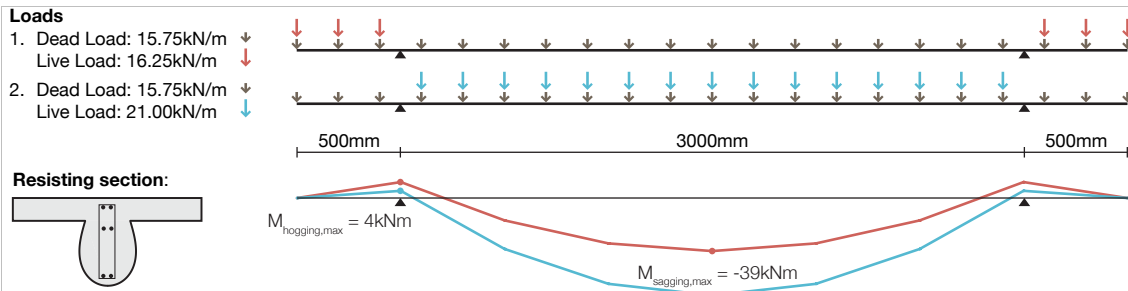


Figure 10 - Load cases and resulting shear and moment envelopes

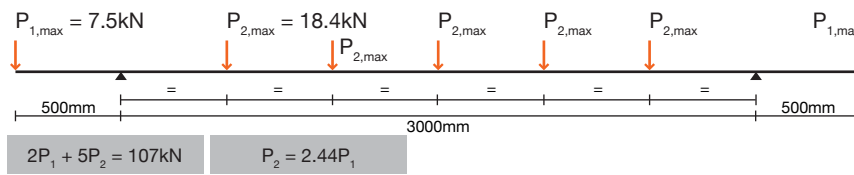


Figure 11 - Test loads

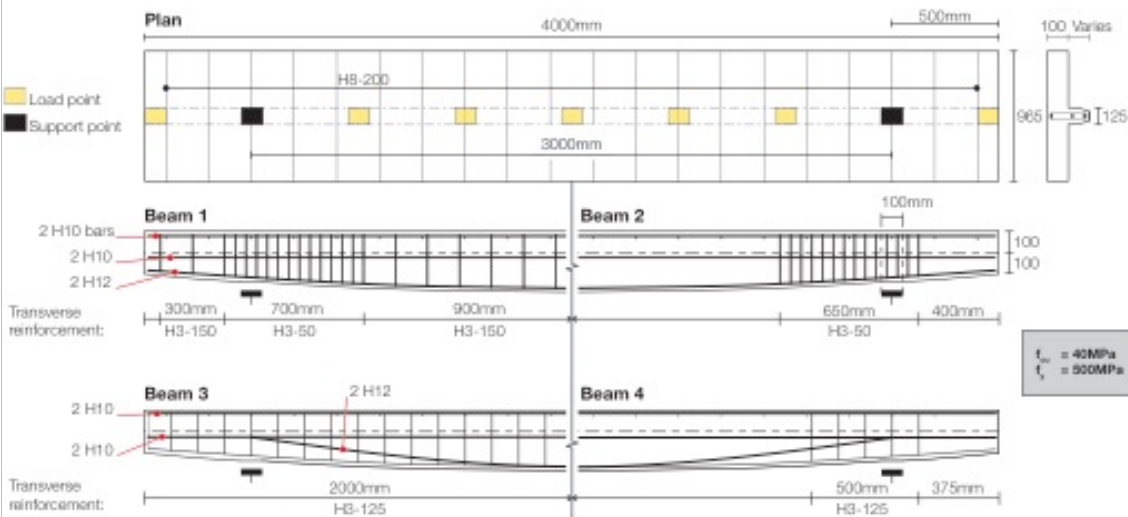


Figure 12 - T-Beam general arrangement

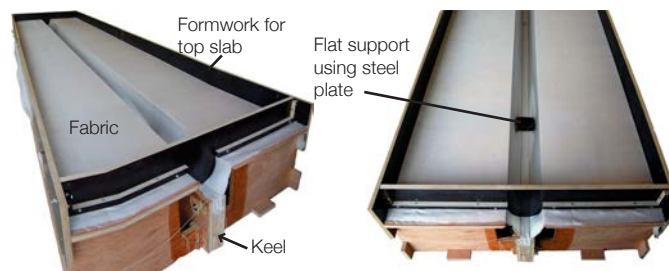
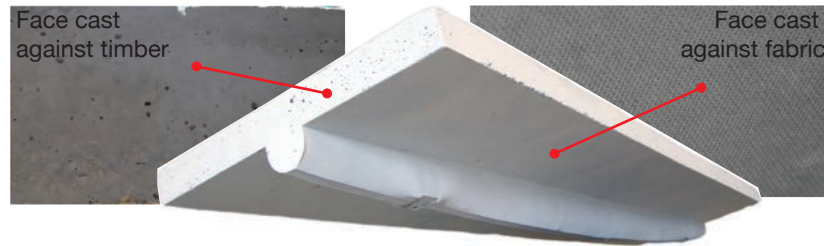


Figure 13 - Keel mould table

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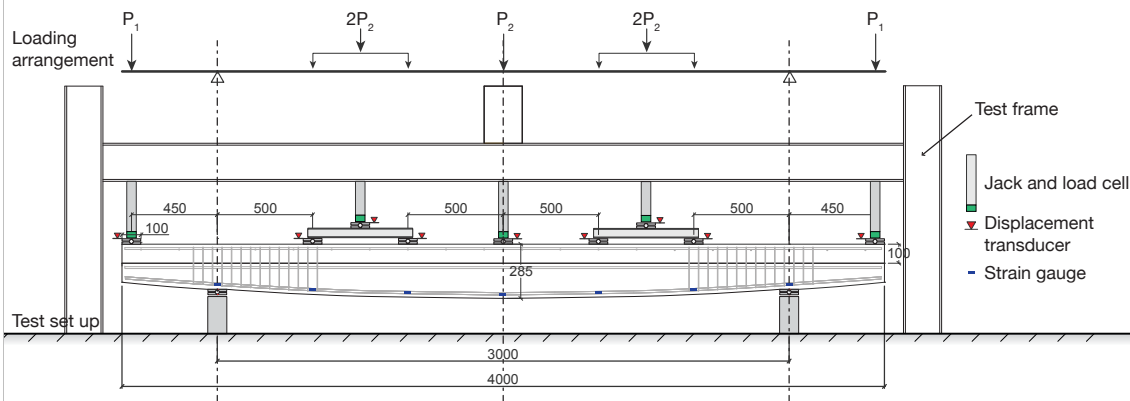


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Figure 14 - T-Beam formed in fabric

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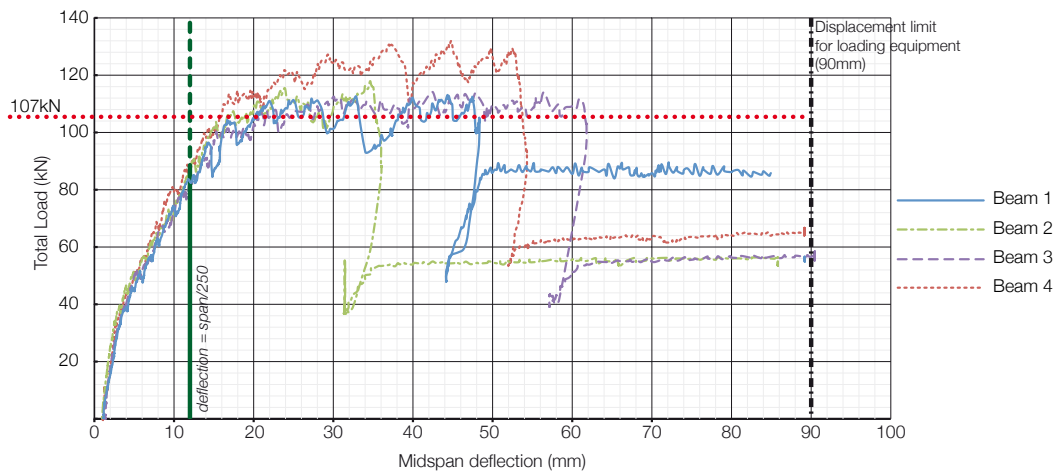


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Figure 15 - Test set up

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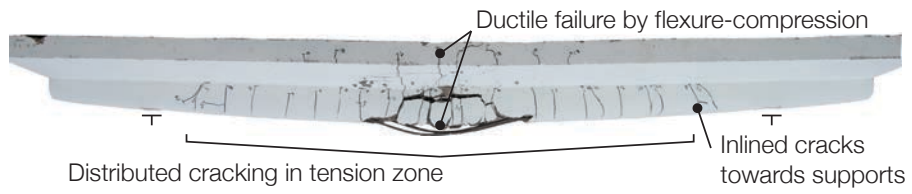
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Figure 16 - Load-Displacement test results, Beams 1-4

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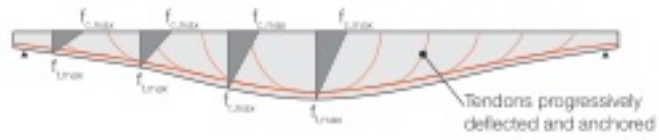


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Figure 17 - Typical failure mode

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Figure 18 - Uniform strength prestressed beams

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

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