Possible solution to past CM examination question

Question 1 - April 2008

Sports Arena

by Dr Peter Gardner

Question 1. Sports Arena

Client's requirements

1. A circular sports arena is to be built on a vacant site; see Figure Q1.
2. The Client has specified that the building shall be 80.0m in diameter internally. The height of the underside of the roof is to be a minimum of 18.0m above the floor in the centre and 20.0m at the perimeter of the arena. The interior of the arena shall be column free.
3. The roof over the arena is to be a lightweight structure and should be of a pleasing appearance.
4. Around the perimeter of the arena is a permanent structure that supports the seating and provides accommodation at level 1 for offices and public amenities and at level 2 for storage. The seating will be made of precast concrete planks which have a maximum span of 8.0m.
5. A 5.0m wide by 4.0m high clear access way is located around the perimeter of level 1 and level 2 shown shaded in Fig.Q1. The area under the sloping seating at level 2 is for storage only and there are no restrictions on the placement of structure in this area.
6. The Client wishes to retain flexibility of use within level 1 of the permanent perimeter structure and has stipulated that the area will be completely unobstructed other than for two lines of internal columns on concentric grid lines measured from the centre of the arena. A minimum spacing of 6.0m between column centres shall be maintained in all directions. A minimum clear height to underside of structure of 4.0m is required throughout. There are no limits on column spacing around the perimeter wall, which is to be clad in masonry.

Imposed Loading

7.	Roof	$0.6kN/m^2$
	Floor levels 2 and 3	$5.0kN/m^2$
	Seating Area	Precast planks dead load of $8.0kN/m^2$ and live load of $5.0kN/m^2$
	Floor level 1	$20.0kN/m^2$

Loadings include an allowance for partitions, finishes, services and ceilings.

Site Conditions

8. The site is level and located on the edge of a major city centre. The site has a public parking area on all sides.

Basic wind speed is 40m/s based on a 3 second gust; the equivalent mean hourly wind speed is 20m/s.

Ground conditions

Borehole 1	Ground - 2.0m	Made ground (fill)
	2.0m-8.0m	Stiff clay. $C=90kN/m^2$
	Below 8.0m	Rock. Allowable bearing pressure = $1000kN/m^2$
Borehole 2	Ground - 4.0m	Made ground
	4.0m -10.0m	Stiff clay. $C=80kN/m^2$
	Below 10.0m	Rock. Allowable bearing pressure = $1000kN/m^2$

Ground conditions change linearly between the 2 boreholes and groundwater was not encountered.

Omit from consideration

9. Detailed design of staircase, precast seating planks and specialist finishes to level 1 floor.

continued overleaf

SECTION 1 **(50 marks)**

a. Prepare a design appraisal with appropriate sketches indicating two distinct and viable solutions for the proposed structure including the foundations. Indicate clearly the functional framing, load transfer and stability aspects of each scheme. Identify the solution you recommend, giving reasons for your choice. (40 marks)

b. After the design has been completed, the Client advises you that he wishes to hang a large advertising and lighting box weighing 50 tonnes from the middle of the roof. Write a letter to the Client explaining how this might be achieved. (10 marks)

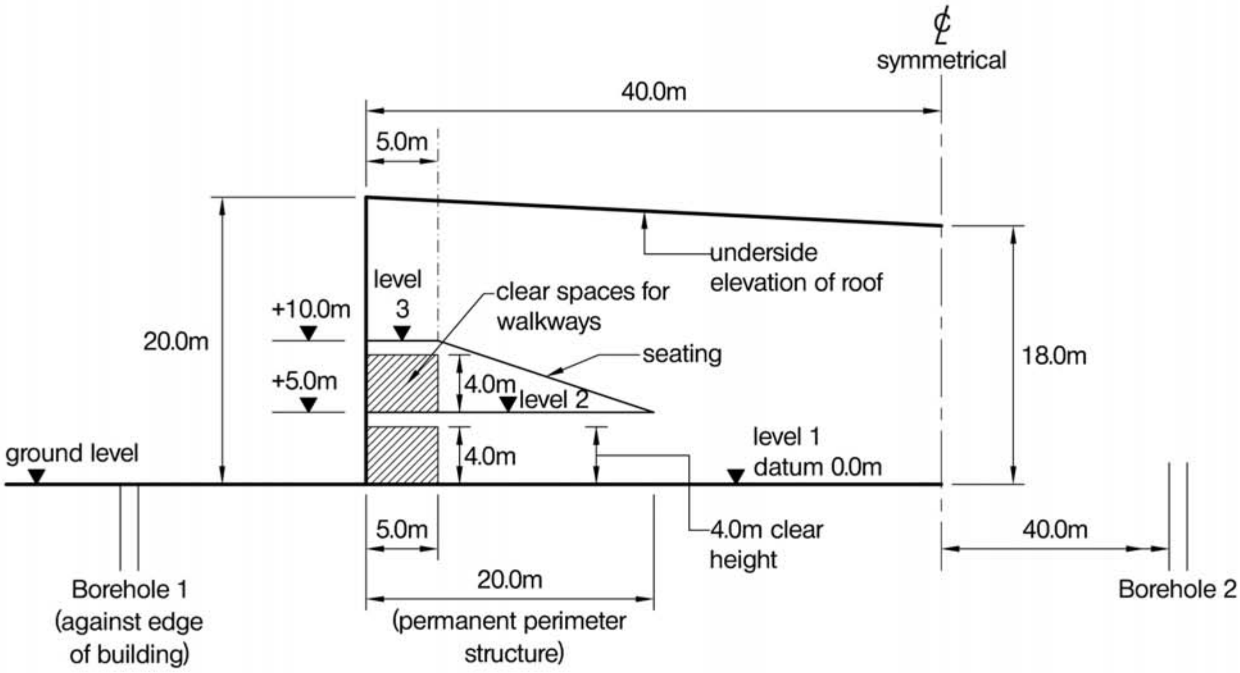
SECTION 2 **(50 marks)**

For the solution recommended in Section 1(a):

c. Prepare sufficient design calculations to establish the form and size of all the principal structural elements including the foundations. (20 marks)

d. Prepare general arrangement plans, sections and elevations to show the dimensions, layout and disposition of the structural elements and critical details for estimating purposes. (20 marks)

e. Prepare a detailed method statement for the safe construction of the building and an outline construction programme. (10 marks)



TYPICAL SECTION THROUGH ARENA

NOTE: All dimensions are in metres

FIGURE Q1

Introduction

This is a relatively straightforward question but it concerns a very large, long-span structure which is likely to be outside the experience of most graduate engineers. It consists of a circular sports arena of 80 metres diameter with an unobstructed/unsupported clear span and a permanent internal perimeter structure, primarily to provide seating, but also circulation walkways and storage.

The roof span contains the greatest complexity. Questions of this nature, with a fixed geometry and a large single span, at first reading can appear to offer very limited options for alternative schemes; however a little thought will often provide distinct structural options. This thinking process should take place very early on in your initial assessment of a question. If you're really in a situation where the brief limits you to a single "obvious" solution then you should think very carefully about continuing, as the questions clearly ask for "two distinct and viable solutions". In this case I believe there are many clear viable alternatives within the constraints of the question.

The issues

- Circular building of 80 metres diameter.
- No internal support at all.
- Variable clear internal height.

- Permanent perimeter structure providing seating, offices, circulation and storage.
- Maximum span of 8 metres for seating (probably safest to make any support with a maximum spacing of 8 metres).
- Two clear access walkways, both 5m x 4m.
- Storage area under the seating has no structural restriction (requirement five)

- Potentially contradictory requirements in relation to level one of the permanent perimeter structure with requirement for it to be unobstructed other than for two lines of internal columns on concentric circular grids (requirement six).
- A minimum of six metres between columns in all directions. A minimum clear height to the underside of both level one and level two structures of 4 metres (consistent with requirement for walkways).

- There are no limits on external columns.
- External elevation to the masonry (stability system?)

- There are no constraints in relation to the site (vacant and accessible).

- Substantial quantity of made ground, overlying stiff clay which itself overlies rock with a substantial ground bearing pressure.
- Profile varies across the site, with no ground water.
- We are likely to have a substantial structure which should probably be founded on the rock.
- The depth of made ground will necessitate an engineered ground floor slab.

Interpretation of the brief

The question probably breaks down to four sections, with only the main roof structure likely to cause any significant difficulty. The four elements are: the 80 metres clear span roof, the seating area, the stability system and the perimeter wall, the foundation system & ground floor.

As far as the roof is concerned, we have a large span with a varying clear height. This allows us to provide greater depth in the centre, thus although it's not a requirement in terms of satisfying the brief, it would seem sensible to follow the internal profile. It would be difficult to provide a satisfactory answer to this question without providing significantly different structural schemes for the roof.

There is no constraint on the external dimensions of the structure, allowing us a completely free hand outside the envelope specified in the question.

The walkways and seating provide the only significant constraints in terms of the brief, but there is nothing here that should cause us any difficulty. This element could form part of the overall stability system, or could just satisfy its own functional requirements.

The whole structure is clad in masonry, the support of which will need to be considered.

The superstructure and two distinct and viable solutions

Despite the structure’s size and pre-defined geometry there is significant possible variation in the superstructure and the associated stability system. My initial thoughts go along the lines of using the circular shape to provide a ring beam to resist forces from the roof structure (arch etc), or a relatively simple beam and stick with an independent stability system, or some variant on a portal frame. Even at the preliminary stage, there are so many possibilities that the problem becomes narrowing them down in a form that can be presented in a time-constrained answer, rather than scratching your head for a second scheme.

Although the geometry (circular structure) provides opportunities for a 3D structure consisting of radial elements, it also gives us the difficulty of multiple beams meeting at the centre. This is likely to be an issue for every option other than simple 2D frames. This may lead us to consider some form of central ring beam which picks up any structural elements converging at the centre, but clearly it would be very difficult to transmit bending with this configuration.

Developing the ring beam idea, leads us to a variety of options of domes or arches in compression where the ring beam resists the horizontal thrust, or tension structures where the ring beam holds the roof elements apart.

A combination of individual trusses, supported on the lattice stanchions would provide a very straightforward and simple-to-analyse arrangement.

Some form of portalised truss would provide inherent stability, and could easily accommodate the spans we are dealing with. This could be modified to a three pinned arch, or a combination of towers and cables supporting a light-weight roof structure.

The geometry is well-suited to a true 3D roof, whether it be an arch, a tension structure or a more traditional 3D space frame, but of course this arrangement would be virtually impossible to design by hand (for the purposes of the exam).

Drainage could be an issue with some structural forms and should be taken into account.

The diagrams following this commentary develop some of these ideas.

Some of the structural arrangements proposed may be susceptible to wind up-lift. If this results in load reversal, and you haven't identified this possibility, you have a potentially serious flaw in your proposal. This is always an issue to keep in the back of your mind.

Stability

There are two fundamental options for the stability system, either utilising a beam and stick arrangement for the principal structure, which needs an independent stability system, or alternatively using frames, that due to their geometry, have inherent stability.

The shape of the building and the lack of any large openings means there is ample opportunity for bracing between the columns, and in the roof. If frames are used that have inherent stability (three-pinned arch or portal frame), additional bracing should be provided in the walls and roof for torsional resistance and overall robustness.

The ground conditions, foundations and ground floor slab

The ground conditions are relatively straightforward, with a thick layer of made ground over the site and rock below at a depth of 8 - 10m. Bearing in mind the size of the structure, it would be sensible to go straight on to the rock.

The rock is only 10 metres below ground level, and therefore some form of pad foundation would be perfectly feasible, but in reality this would just be a variation on a piled solution (it's only the construction method that would be different, the structural action would be the same, albeit that pads would provide a potentially greater area per foundation than would be readily achievable with a pile). Assuming that we have sufficient variation in the superstructure to satisfy the "two distinct and viable schemes" requirement, it would probably be sensible to propose a single foundation solution, with a discussion of possible variations on that theme.

The perimeter wall will need a significant foundation, probably using either a ring of piles, or “trench fill” constructed directly off the rock.

Because of the thickness of the made ground, the ground floor slab will need to be an engineered solution (although the surface could be grass in which case it could be potentially be applied to the existing material). Assuming the arena surface is solid, the ground floor slab and the walkways could potentially be supported from the clay (not the fill), but it would probably be more straightforward to pile into the rock for the whole structure. This would avoid any issues of differential movement between the clay and the rock. Ground improvement could be considered.

The letter

The letter is straightforward in that the client wishes to hang a large advertising and lighting box from the middle of the roof, so superficially the letter could just explain how this might be achieved. However, we have a very large weight in the middle of an 80 metres span roof, which is going to have considerable implications for the structure. A client may not realise the implications of such a request and therefore some lateral thinking in relation to alternatives, to minimise the effect on the structure (in addition to explaining how the actual request might be achieved), could be beneficial.

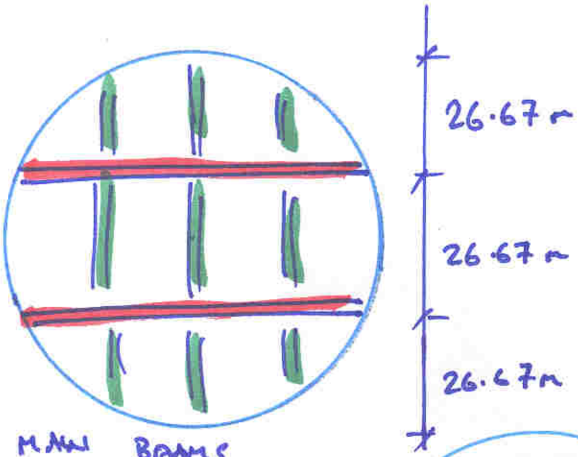
There are many issues relating to the provision of the advertising box which gives scope for well-written helpful advice in the form of a letter to your client. As is always the case in these situations, part of the answer must respond to the client's request, whatever the structural consequences (ie it's not for the client's engineer to say this cannot be done, but to draw the client's attention to the consequences of the proposal, and offer alternatives which may produce a better/cheaper solution).

The issues that you may care to think about, and potentially build into your answer for this part of the question, could include: the significance of hanging 50 tonnes from the middle of a large clear span and the practicality of doing this as requested, deflection, investigating the possibility of achieving the same objective with less weight, providing smaller multiple advertising/lighting units which could be located away from the middle of the roof, providing an independent support system (possibly cables) with the implications of restricted visibility.

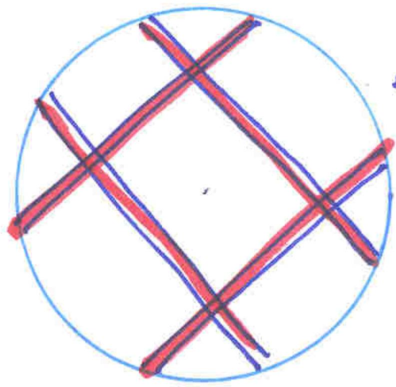
Summary

The size of the overall structure, and the requirement for an 80 metres clear span, makes this a daunting structure under any circumstances, and one that is likely to be outside the individual experience of most graduate engineers. However the brief is straightforward, and doesn't contain anything that should give us particular cause for concern. As long as a candidate can find "two distinct and viable solutions", which I think the analysis above suggests is relatively straightforward, then there is no reason why any reasonably experienced candidate should not achieve a comfortable pass with this question.

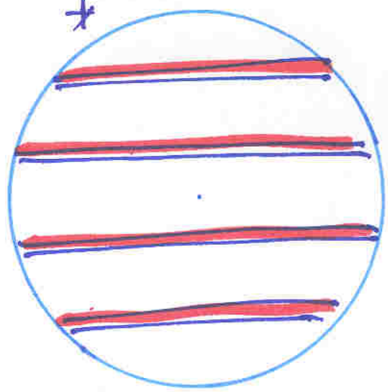
PLAN OPTIONS



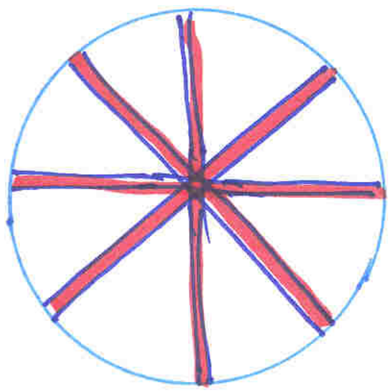
TWO MAIN BEAMS WITH SECONDARY BEAMS



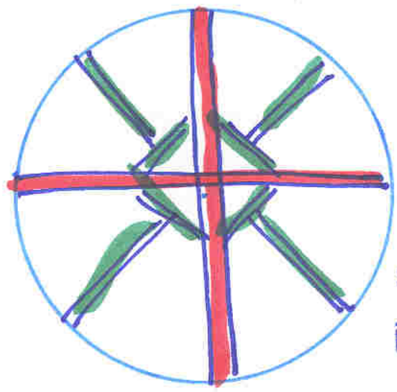
FOUR MAIN BEAMS/FRAMES



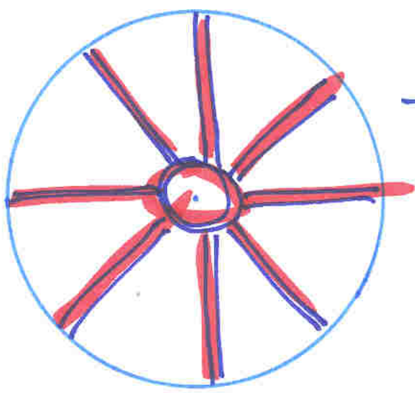
FOUR MAIN BEAMS/FRAMES



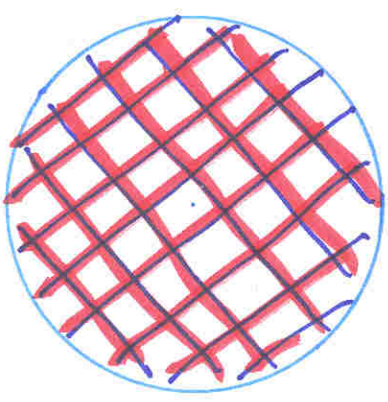
FOUR MAIN BEAMS/FRAMES (CENTRAL DETAIL?)



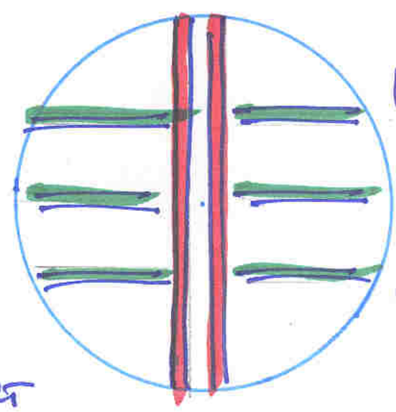
FOUR MAIN BEAMS WITH SECONDARY BEAMS



THREE PINNED ARCH WITH CENTRAL RING BEAM.



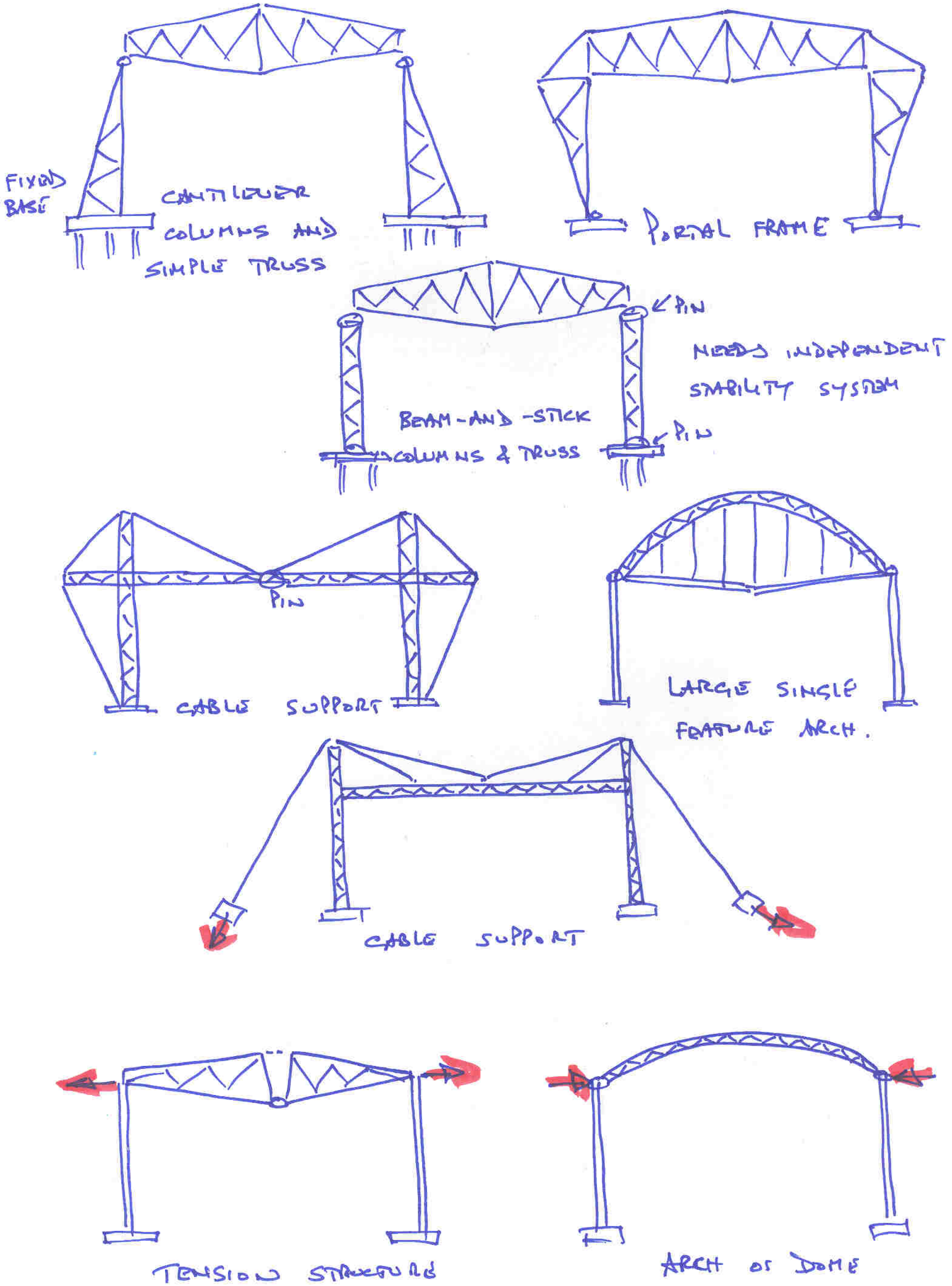
SPACE FRAME ROOF (3D TRUSS)



LARGE CENTRAL SUPPORTS (TRUSS OR ARCH).

MAIN SUPPORT

SECONDARY SUPPORT



FRAME OPTIONS