

The **Institution** *of* **Structural** **Engineers**

Possible solution to past CM examination question

Question 1 - April 2011

Theatre

by Dr Peter Gardner

The information provided should be seen as an interpretation of the brief and a possible solution to a past question offered by an experienced engineer with knowledge of the examiners' expectations (i.e. it's an individual's interpretation of the brief leading to one of a number of possible solutions rather than the definitive "correct" or "model" answer).

Question 1. Theatre

Client's Requirements

1. A new theatre and arts complex is to be built in a city centre: see Fig. Q1. The theatre is to be located below ground level with practice facilities, office space and eating facilities above.
2. A clear space must be provided within the performance area of the theatre bounded by gridlines 1 and 3 and gridlines B and C. No permanent structure may be provided in this space. At either end of the theatre space there is a service zone where there are no structural restrictions. Access for maintenance must be provided to all parts of each zone.
3. Above the theatre is an internal/external dining space at elevation +0.0m. The architect has specified that the only structural elements permissible on grid line 2 between gridlines B and C are slender columns. No bracing or walls are permitted.
4. A double storey rehearsal studio is at elevation +4.5m. The area available for rehearsal shall be maximised by limiting columns to a minimum. Two floors of offices are located above the rehearsal space where there are no specific restrictions on structure.
5. The architect wants to allow as much light as possible into the building on Gridline 2 and has stipulated that more than 70% of the elevation shall be glazed between gridlines B and C.

Imposed Loading

- | | |
|-----------------|--|
| 6. Roof | 1.5 kN/m ² |
| Floor loading | Ground and theatre floors – 10.0 kN/m ² |
| Elevated floors | 5.0 kN/m ² |

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

Site Conditions

7. The site is level and located next to a busy road. Excavations may not approach the road closer than 1.0m. Basic wind speed is 40m/s based on a 3 second gust; the equivalent mean hourly wind speed is 20m/s.
8. Ground conditions – The site is level and the single borehole at the centre of the building is representative of the whole site. Ground water was found at -4.0 m

Borehole 1	Ground – 3.0m	Made ground
	3.0 m – 8.0 m	Stiff clay. C = 80 kN/m ² Ø=0
	Below 8.0 m	Rock. Allowable bearing pressure = 800 kN/m ²

Omit from consideration

9. Detailed design of stairs.

SECTION 1

(50 marks)

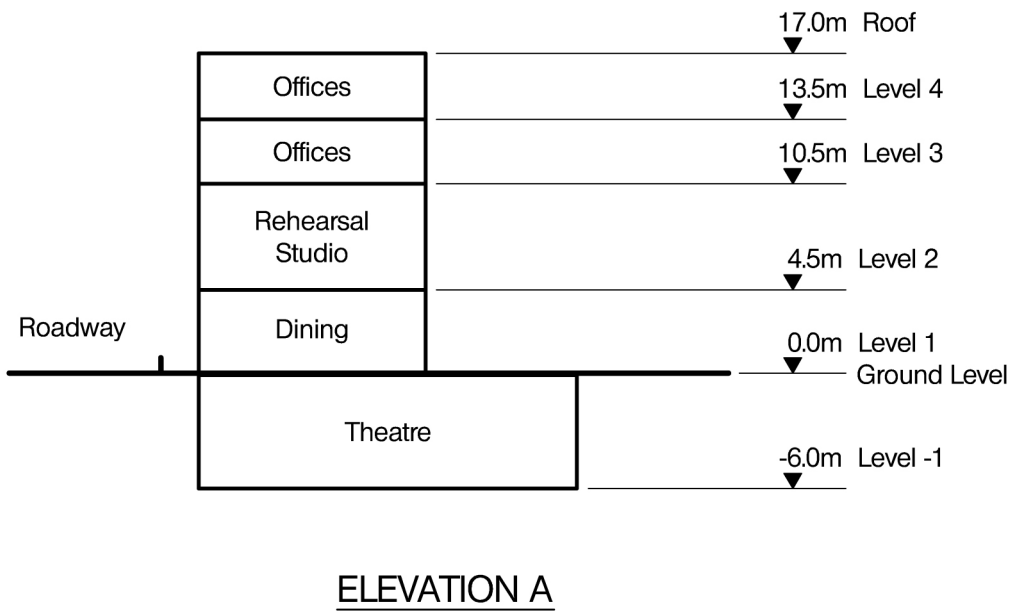
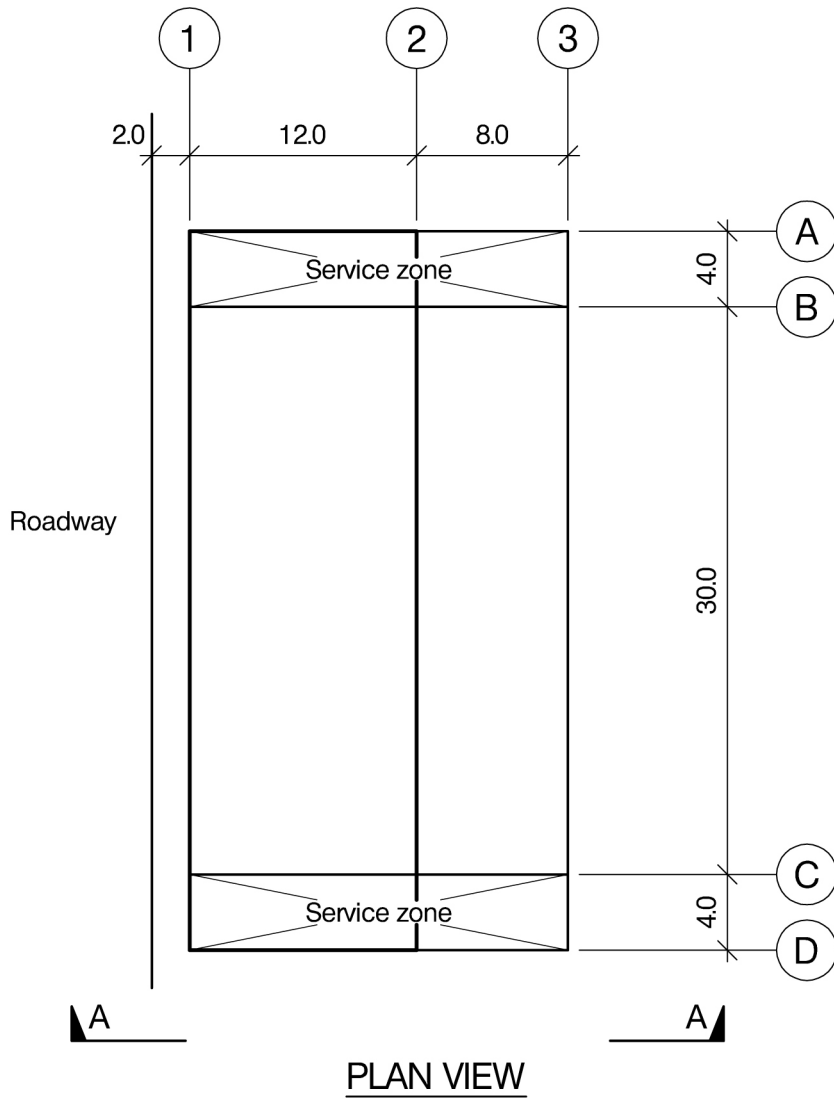
- a. Prepare a design appraisal with appropriate sketches indicating two distinct and viable solutions for the proposed structure. Indicate clearly the functional framing, load transfer and stability aspects of each scheme. Identify the solution you recommend, giving reasons for your choice. (40 marks)
- b. After the design has been completed, the client advises that the rehearsal studio is to be column free internally. Write a letter to the client explaining what impact there will be on the design and 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, including details of any temporary propping of the structure required above ground level during construction. (10 marks)



NOTE: All dimensions are in metres

FIGURE Q1

Introduction

This question relates to a subterranean theatre with a four-storey structure above ground level, comprising an open-plan dining area, rehearsal studio and offices on the upper two levels.

The brief

The client's requirements are:

- Clear space provided within the theatre performance area between grid lines 1/3 and B/C. This effectively means no supporting structure away from the perimeter, other than in the two service zones.
- At level zero the dining room extends outside. There are no structural elements permitted on grid line 2 between B and C, other than slender columns [ie an open facade allowing slender columns but no bracing (again this restriction does not apply to the service zones)].
- A double storey-height rehearsal studio with minimal internal columns.
- Two floors of offices with no specific restrictions.
- The facade on grid line 2 is required to let in as much light as possible and therefore more than 70 per cent of the elevation between grid lines B and C must be glazed.

The issues

From the brief, and the summary above, it is clear that the examiners are looking for a design that will necessitate limited structural members in certain areas connected with the theatre, dining area and rehearsal studio, which will require transfer structures.

No internal support is allowed within the theatre area, necessitating a significant structural arrangement to support the building above, particularly along grid line 2.

The dining area has a restriction along grid line 2 where no bracing or walls are permitted, however there is no restriction on the number of [slender] columns, allowing the columns from above to run through to the theatre roof (although common sense may suggest these should be minimised).

The rehearsal studio is to have a minimum number of internal columns. The literal interpretation of "a minimum" is none, if this is practical (which it is in this case). Therefore, it seems reasonable to work on the basis that not all internal columns from the offices above should be

run-through. However a limited number of columns are desirable (to avoid over sized floor beams). It should also be noted that section 1b relates to a client change where the rehearsal studio is required to be column-free, reinforcing the interpretation that some columns are expected/desired in the initial design.

The requirement for glazing on grid line 2 doesn't necessarily prohibit bracing, but commonsense would suggest that aesthetics should be taken into account and heavy structural members should be avoided. However, all the restrictions relating to the structure and glazing apply only between grid lines B and C, therefore stability could be afforded by bracing or cores in the two service zones, allowing the remainder of the elevation on grid line 2 to be completely glazed, with only the columns and floors being visible.

There are no clear heights specified for any of the usable spaces, but level heights are given. This does place practical limitations on the depth of each floor zone, particularly in the theatre where there is only six metres available and a substantial structure may be required in the ceiling to support the building above.

The ground conditions are quite straightforward with three metres of made ground, a further five metres of stiff clay and rock at eight metres (with a specified ground bearing pressure). Bearing in mind the theatre floor is at -6.0m, once the foundations and theatre floor have been constructed there will only be a short additional distance to reach the rock. Curiously, ground water is specified at four metres, which has implications, particularly during the construction phase (possible flotation in the temporary condition, depending on the construction techniques employed) and waterproofing the below-ground structure. There may be contaminants in the made ground.

The building is located in a city-centre and there is a roadway adjacent to grid line 1, which will have an impact on the construction and the structural proposal. The roadway is two metres from grid line 1 and the brief stipulates that the excavations must not be closer than one metre from the road, allowing one metre for the construction of the basement retaining wall.

Structural options

There are various options, that address the constraints and lead to viable solutions:

Option 1. Probably the simplest option would be the provision of transfer beams at ground-level supporting the building above (particularly along grid line 2). The principal concern with this solution is the depth of the beams, particularly bearing in mind that the theatre has a total height of six metres. A single 30 metre-span beam running along grid line 2 would require substantial depth but an alternative would be a series of beams spanning 20 metres parallel to grid line A. Additional structural efficiency could be afforded by a 2D grillage, although the additional complexity of moment resisting joints in two directions probably wouldn't justify the gain, especially as there is no limit to the number of beams that could be installed running parallel to grid line A. See figure 1.

Option 2. An alternative would be to support the theatre roof from above. There are various options, the most obvious of which is a Vierendeel girder running along grid line 2. It could be positioned at any of the four levels but the columns in the restaurant area are required to be "slender" so it would be sensible to position any girder in one of the upper levels. The principal problem with a Vierendeel girder is deflection, especially as this elevation is effectively fully glazed. There is no reason why the Vierendeel should be restricted to one level, therefore my proposal would be to specify a moment resisting frame across the three upper levels, the complication and cost being justified on the basis of smaller member sizes and reduced deflection when compared with a similar arrangement limited to one level. This would enable hangers to extend from the bottom of the Vierendeel to support the theatre roof. See figure 2.

Option 3. A variation on option two would be to supply a truss at one level spanning between grid lines B&C. This clearly would have a visual impact, as the diagonals would be seen through the glass facade, but this would be a stiffer and cheaper option than the Vierendeel girder, as long as the architect/client is content to see the structure. See figure 3.

Option 4. Another option would be to provide a truss at roof level with hangers supporting the floors at each level, down to the theatre roof. There is no overall height restriction on the building but clearly this would have a visual impact. It could be left exposed and made an architectural feature, or clad to appear either as a parapet or as a false roof. Stability of the top flange should be recognised as an issue (easily dealt with utilising support struts back to the roof). See figure 4.

Option 5. Another variation would be to install an arch spanning the full length of the building with hangers/struts supporting the various floors. As there is no restriction on structure between grid lines A/B and C/D, the arch could start at ground level without infringing the requirement for "no structure other than slender columns" in the restaurant entrance. It would clearly be an architectural feature intentionally seen through the glass facade. See figure 5.

Option 6. A final variant would be diagonal ties extending from the roof across three levels (complying with the specific requirement for an open restaurant entrance). This would have the effect of reducing the span of the edge beam on grid line 2 to ten metres. As with option 5, this could be made an architectural feature. See figure 6.

Stability.

The service zones could be constructed as stiff cores with all lateral loads being transferred to them via reinforced concrete floors acting as diaphragms.

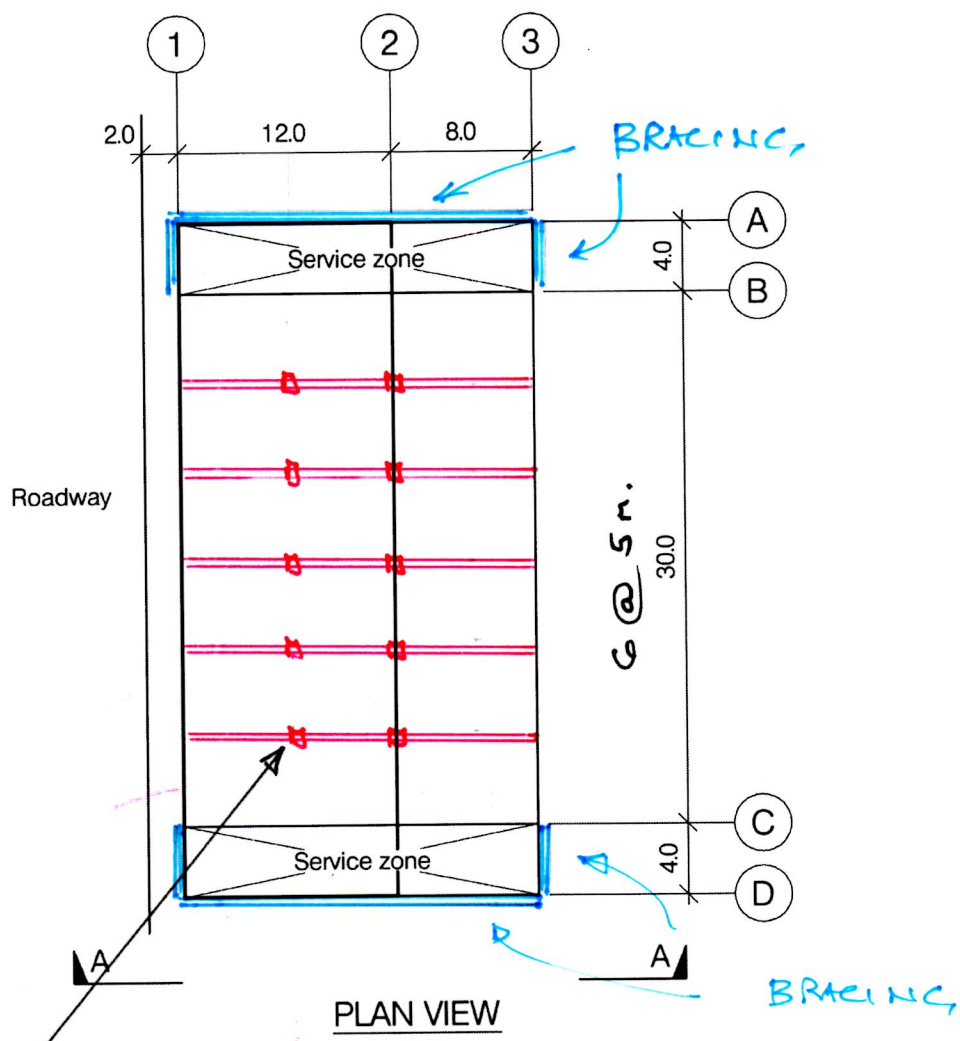
The Letter

The letter requires a response to the scenario that after the design has been completed the client wishes the rehearsal studio to be column free. Depending on exactly how the remainder of the building has been designed, this is unlikely to have an impact on the stability system but will require additional transfer structures to carry the load from internal columns in the office areas to the perimeter structure.

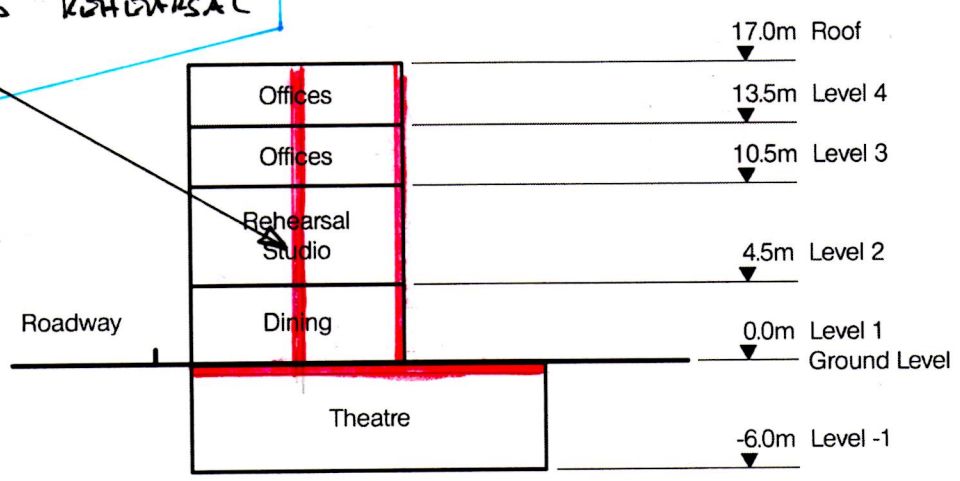
Providing deep beams in the floor of level three would be one option, although this would reduce the overall height of the rehearsal studio. Another option would be to support any central columns in the offices with either a longitudinal truss within the office corridors, or a truss placed on the roof. Although all these options could be explained in your response to the client, the one chosen would logically relate to your chosen scheme in section 1a.

Summary

From my perspective this is an ideal question offering some level of difficulty, which provides: a vehicle to demonstrate your engineering knowledge, no complications in the brief, no undue complexity and critically offering at least two "distinct and viable" solutions. For these reasons it should be possible to produce a comprehensive and complete solution affording a comfortable pass mark.

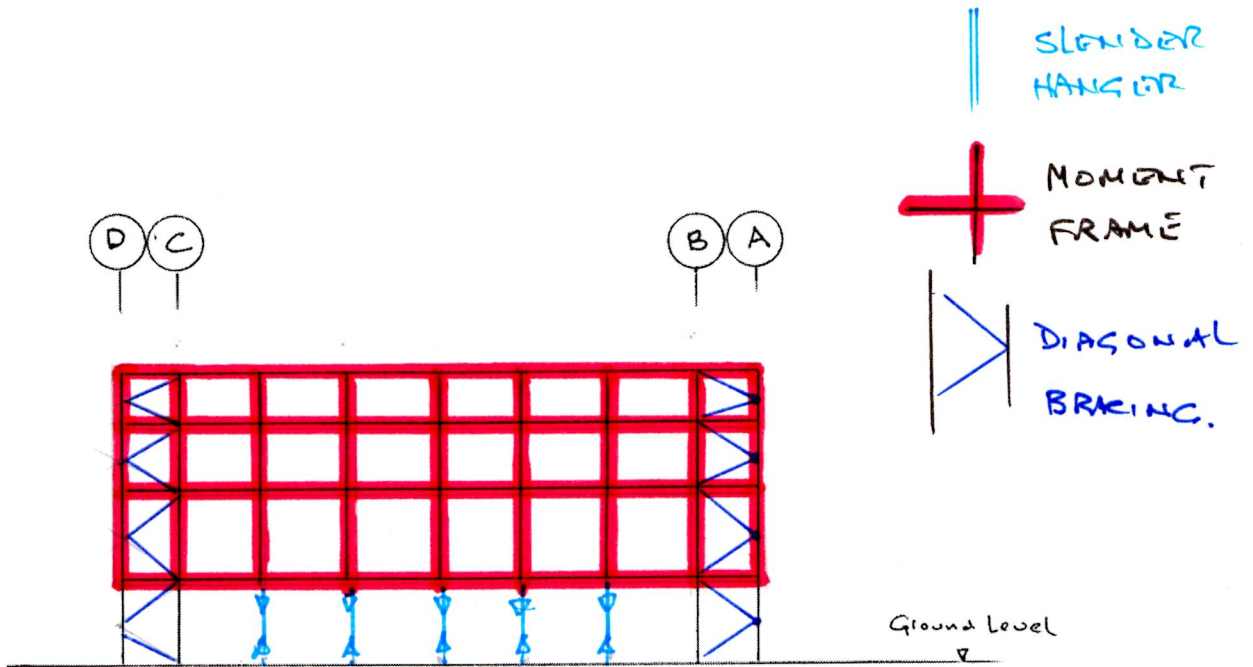


ALTERNATE COLUMNS OMITTED IN REHEARSAL STUDIO.



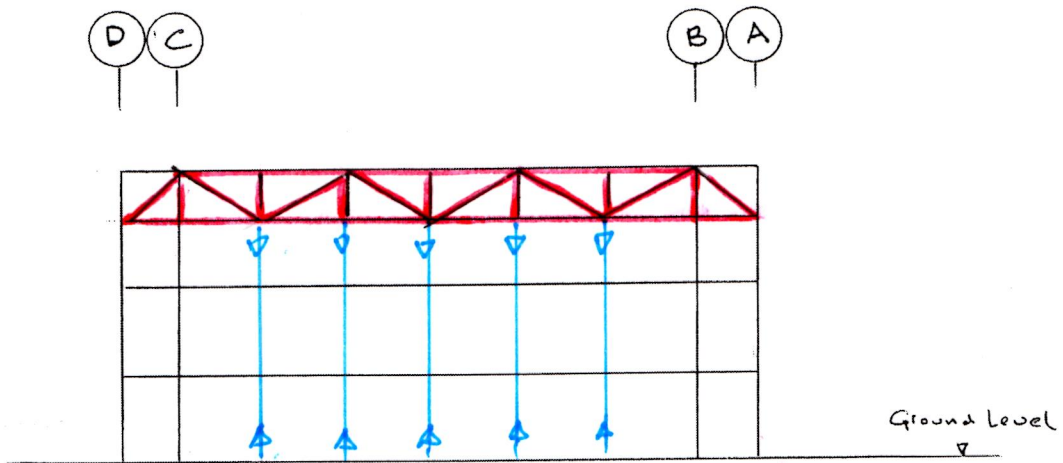
NOTE: All dimensions are in metres

FIGURE Q1



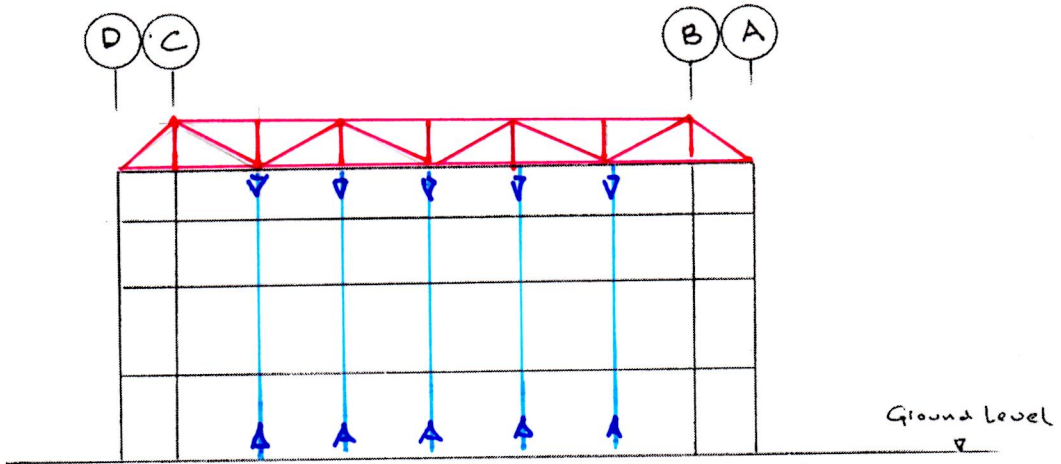
Provides support
for theatre roof

FIGURE 2



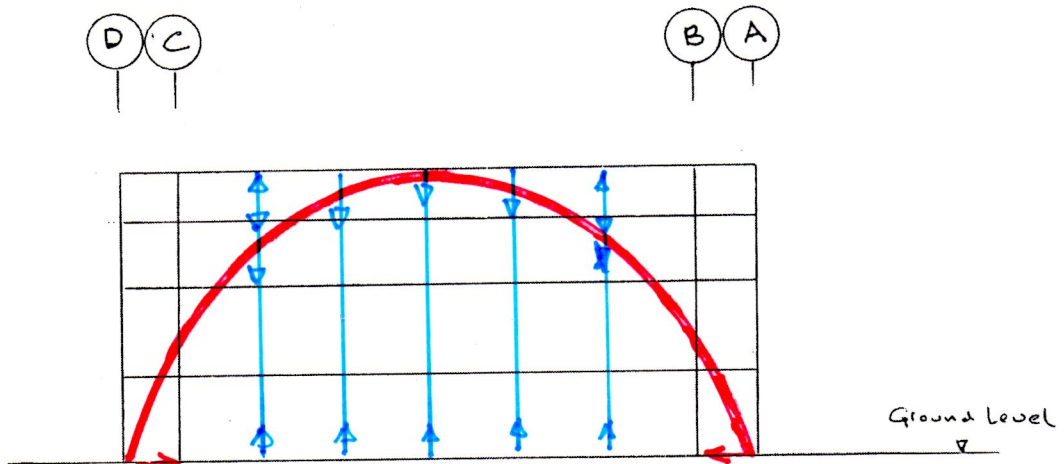
Provides supports
for theatre roof.

FIGURE 3.



Provides support for
theatre roof.

FIGURE 4



Provides support for
theatre roof.

FIGURE 5

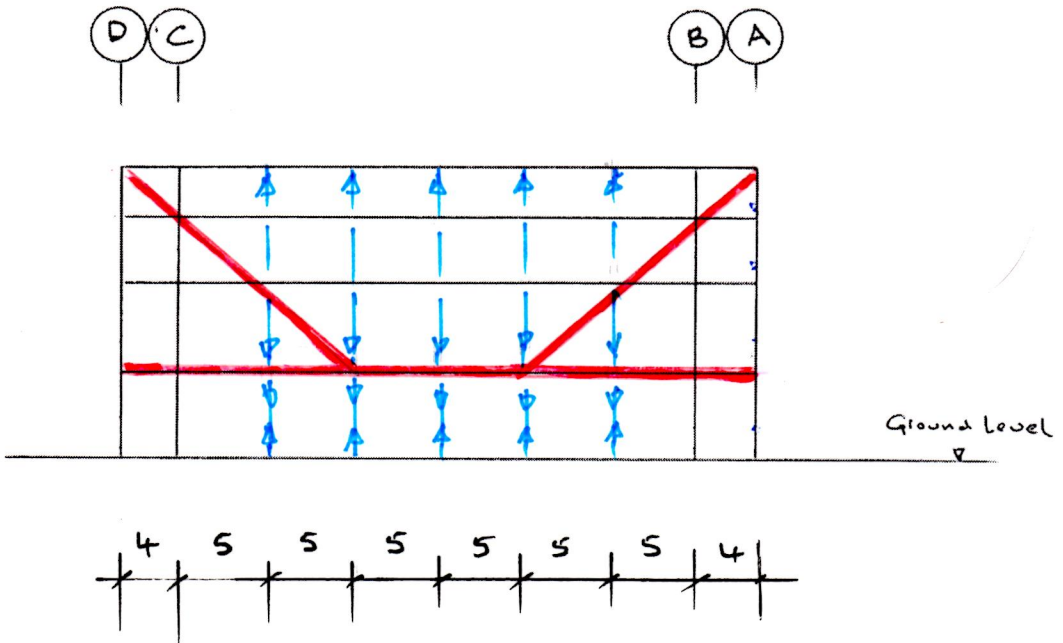


FIGURE 6.