Lecture 1B:
STEEL CONSTRUCTION:
INTRODUCTION TO DESIGN

TECHSummer School at WUST, Steel Structures 22-23.07.2019

Dr Michal Redecki

STEEL CONSTRUCTION: INTRODUCTION TO DESIGN

Lecture 1B.1 : Process of Design

SUMARRY: The lecture begins by considering a definition of design and some objectives. It discusses how a designer can approach a new problem in general and how a structural designer can develop a structural system. It concludes by considering differences of emphasis in design approach for different classes of structure.

1. DESIGN OBJECTIVES

The results of successful design in structural engineering can be seen and used by everyone, see Figure 1.

The question is: how can professional designers be developed and eventually produce better designs than those previously encountered, to benefit and enhance the performance of human activities? In particular how can steel be utilised effectively in structures for:

- travelling more easily over awkward terrain, requiring bridges.
- enabling basic industrial processes to function requiring, for example, machinery supports, docks and oil rig installations.
- aiding communications, requiring masts.
- enclosing space within buildings, as in Figure 2.

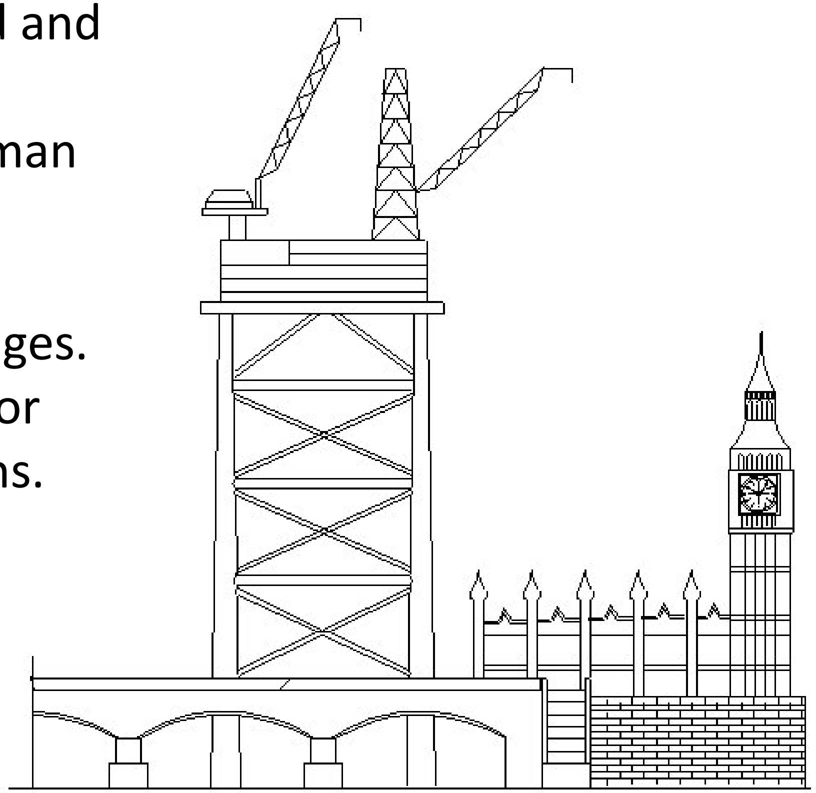


Figure 1 Comparisons of scale: buildings, bridges and offshore platforms

1. DESIGN OBJECTIVES

In particular how can steel be utilised effectively in structures for:

- travelling more easily over awkward terrain, requiring bridges.
- enabling basic industrial processes to function requiring, for example, machinery supports, docks and oil rig installations.
- aiding communications, requiring masts.
- enclosing space within buildings, as in Figure 2.

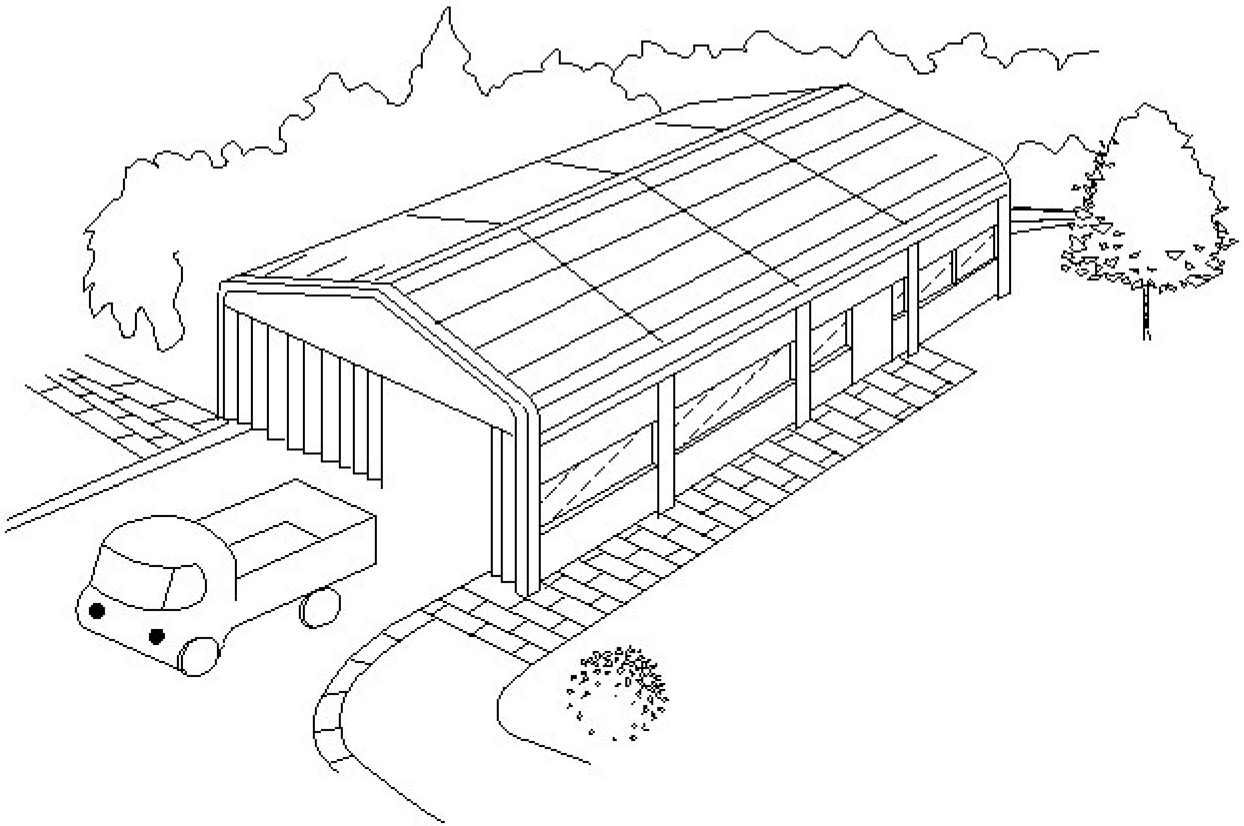


Figure 2 Finished garage

1. DESIGN OBJECTIVES

Design is 'the process of defining the means of manufacturing a product to satisfy a required need': from the first conceptual ideas, through study of human intentions, to the detailed technical and manufacture stages, with the ideas and studies communicated with drawings, words and models.

'Designers'? All people are capable of creative conceptual ideas - they are continuously processing information and making conscious imaginative choices, e.g. of the clothes they wear, of the activities they engage in, and the development of ideas they pursue, causing changes.

In structural design, prime objectives are to ensure the best possible:

- unhindered functioning of the designed artefact over a desired life-span.
- safe construction system, completed on time and to the original budget cost.
- imaginative and delightful solution for both users and casual observers.

These points could possibly be satisfied by either:

- simply making an exact copy of a previous artefact, or,
- 're-inventing the wheel', by designing every system and component afresh.

1. DESIGN OBJECTIVES

Both these extreme approaches are unlikely to be entirely satisfactory. The problem may be slightly different, e.g. the previous **bridge may have stimulated more traffic flow** than predicted. **Economic and material conditions may have changed**, e.g. the cost of labour to fabricate small built-up steel elements and joints has increased compared to the production cost of large rolled or continuously welded elements. **Deficiencies of performance may have been discovered with time**, e.g. vibrations may have caused fatigue failures around joints. **Energy consumption conditions may have changed**, e.g. relating to the global discharge of certain chemicals, the cost of production of certain materials, or the need for greater thermal control of an enclosed space. Finally, too **much repetition** of a visual solution **may have induced boredom and adverse cultural response**, e.g. every adjacent building is produced in the "Post Modern Style".

Civil and structural engineering projects are usually large and occur infrequently, so a disenchanted client will not make a second invitation. Realisation of new theoretical ideas and innovations invariably takes much time; history shows this repeatedly. Thus methodical analysis of potential risks and errors must temper the pioneering enthusiast's flair.

Positive creative solutions must be achieved for all aspects of every new problem. The solutions will incorporate components from the extremes above, both of fundamental principles and recent developments. However, throughout the Design Process it is prudent to maintain a clear grasp of final objectives and utilise relatively simple technical means and solutions.

2. HOW DOES THE DESIGNER APPROACH HIS NEW TASK?

At the outset of a new task an "instant of blind panic" may occur. There are a variety of Design Methods to help progress [4, 5] with the new task, but the following methodical approach is suggested

- Recognise that a challenge exists and clearly define the overall objectives for a design, see Figure 3.
- Research around the task and investigate likely relevant information (Analysis).
- Evolve possible solutions to the task (Synthesis).
- Decide on, and refine, the best solution (Evaluation), establishin clear priorities for action (in terms of manufacture, constructior operation and maintenance).
- Communicate decisions to others involved in the task.

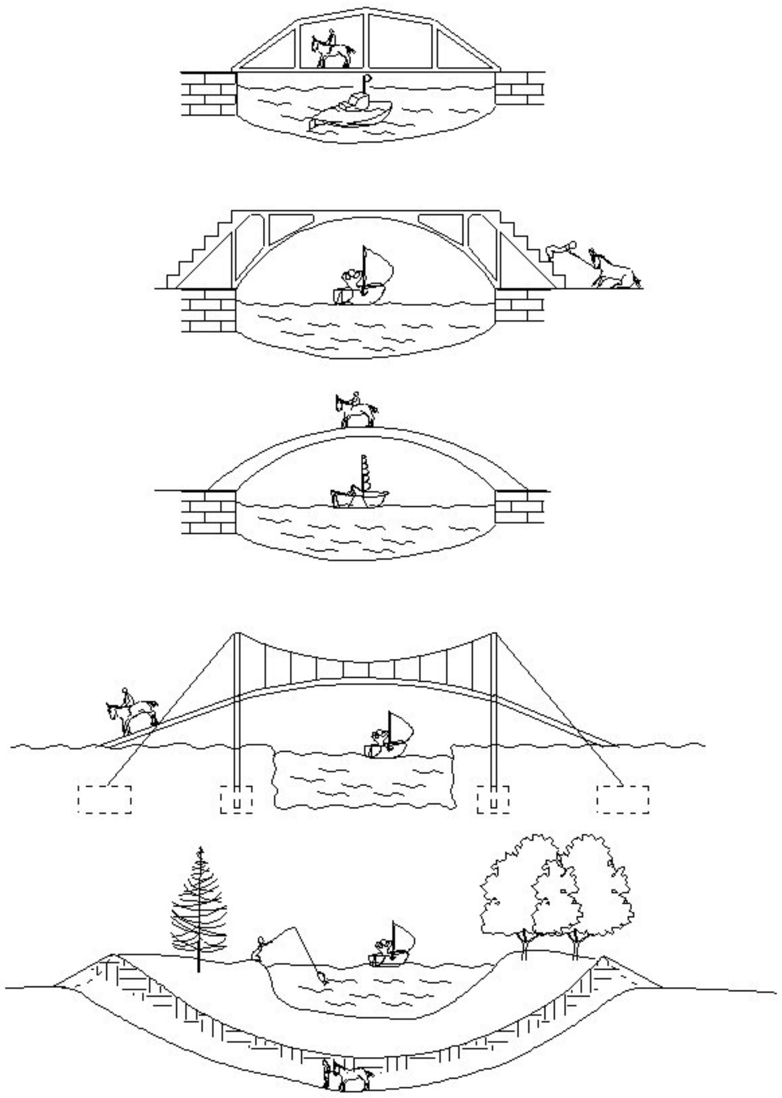


Figure 3 "Define the overall objective" (based on E.Torroja)

2. HOW DOES THE DESIGNER APPROACH HIS NEW TASK?

At the outset, these five phases appear as a simple linear chain; in fact the design process is highly complex, as all factors in the design are interdependent to a greater or lesser degree. Hence there will be many steps and loops within and between the phases, as seen in Figure 4. The first rapid passage through phases 1, 2 and 3 will decide if there is 'any problem', e.g. is the likely traffic flow adequate to justify a convenient but high cost bridge?

All factors and combinations must be explored comprehensively from idea to detail, with many compromises having to be finely balanced to achieve a feasible solution. Ideas may be developed: verbally, graphically, numerically or physically.

The starting point for Analysis may thus be the designer's current preconceived notion or visual imagination, but the Synthesis will reveal the flexibility of his mind to assimilate new ideas critically, free of preconception.

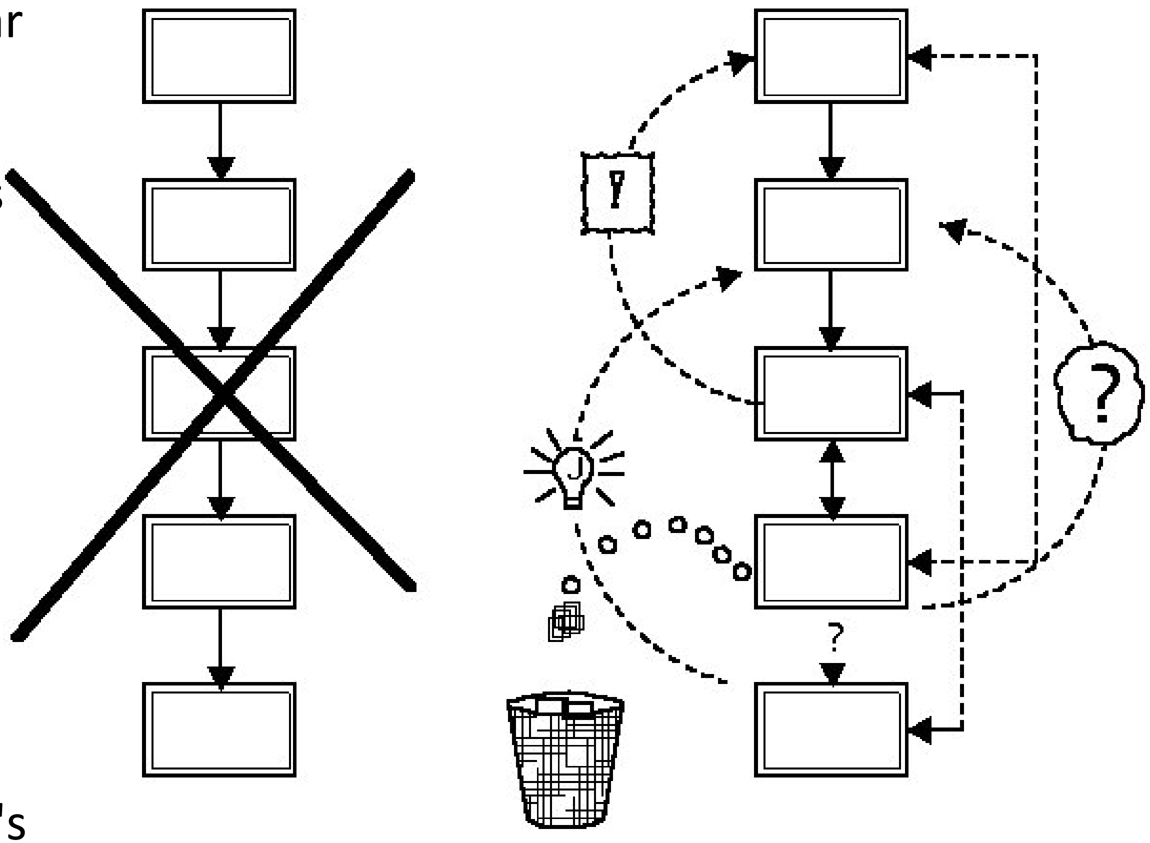


Figure 4 Design phase iterations

3. HOW DOES THE DESIGNER DEVELOP HIS STRUCTURAL SYSTEM?

3.1 Pose an Initial Concept that may well Satisfy the Functions

It is the best idea to start by looking at the functions (performance) required and their relationships. Make a list of individual functions; then generate a 'bubble' (or flow) diagram of relationships between different functional areas to decide possible interconnections and locations, see Figure 5. Find, or assume, suitable plan areas and minimum clear heights of each three-dimensional 'volume of space'. A possible plan layout may then be indicated, noting any particular complications of the site, e.g. plan shape, proximity of old buildings, slope or soil consistency.

Many other plan arrangements will be possible and should be considered quickly at this phase.

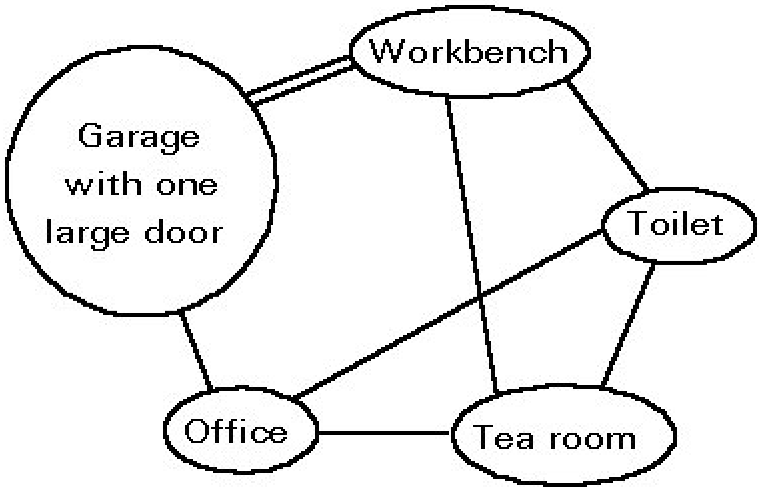


Figure 5 Bubble diagram

3. HOW DOES THE DESIGNER DEVELOP HIS STRUCTURAL SYSTEM?

3.1 Pose an Initial Concept that may well Satisfv the Functions

The requirements of each 'volume of space' and it interfaces must be examined for all functional, co and aesthetic criteria, e.g. what structural applied loads must be resisted; what heating, ventilating, lighting and acoustic requirements are likely to be desired, see Figure 6.

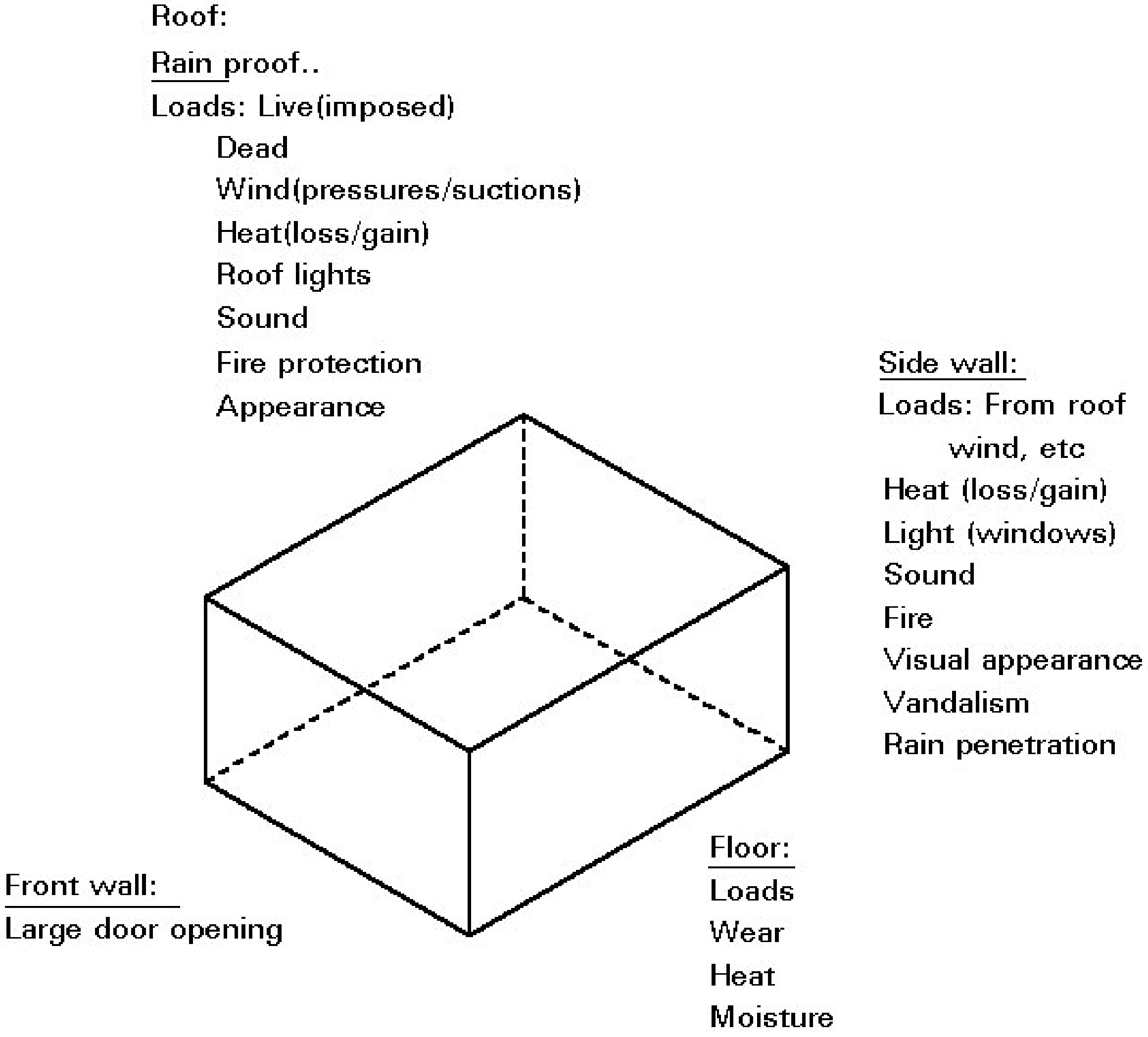
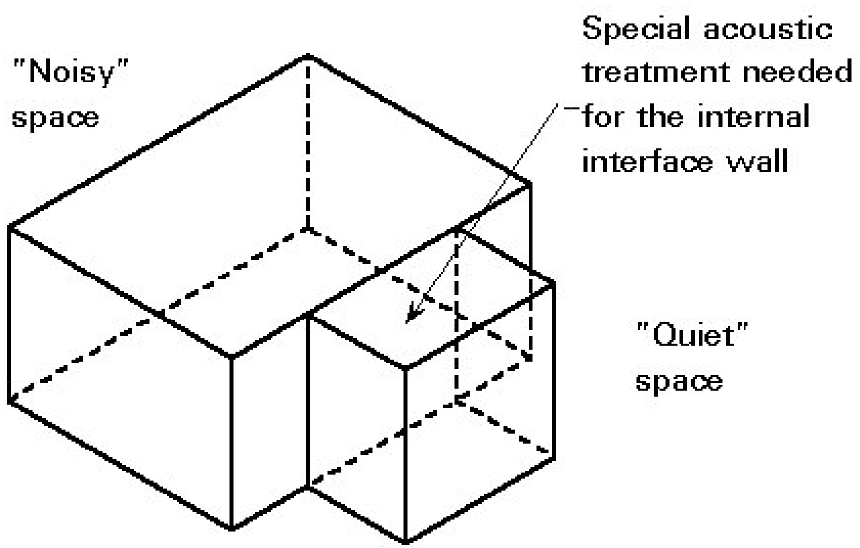


Figure 6 Volumes of space

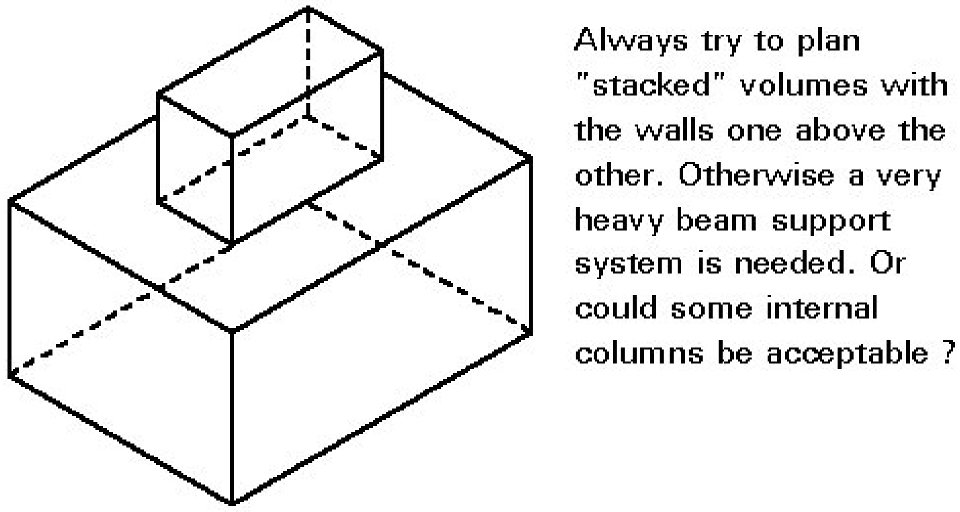
3. HOW DOES THE DESIGNER DEVELOP HIS STRUCTURAL SYSTEM?

3.1 Pose an Initial Concept that may well Satisfy the Functions

The main criteria can easily be recognised and then followed up and tested by numerical assessment. Incompatibilities may be 'designed out' by re-arranging the planned spaces or making other compromises, see Figure 7, e.g. would you accept an office telephone being very close to the workshop drill or lorry engine, without any acoustic insulation?



Special acoustic requirements between volumes



Vertical relationships between volumes.

Figure 7 "Design out incompatibilities"

3. HOW DOES THE DESIGNER DEVELOP HIS STRUCTURAL SYSTEM?

3.1 Pose an Initial Concept that may well Satisfy the Functions

Prepare a set of initial assumptions for possible materials and the structural 'Frame', 'Planar' or 'Membrane' load-bearing system [7] that might be compatible with the 'volumes of space' as shown in Figure 8.

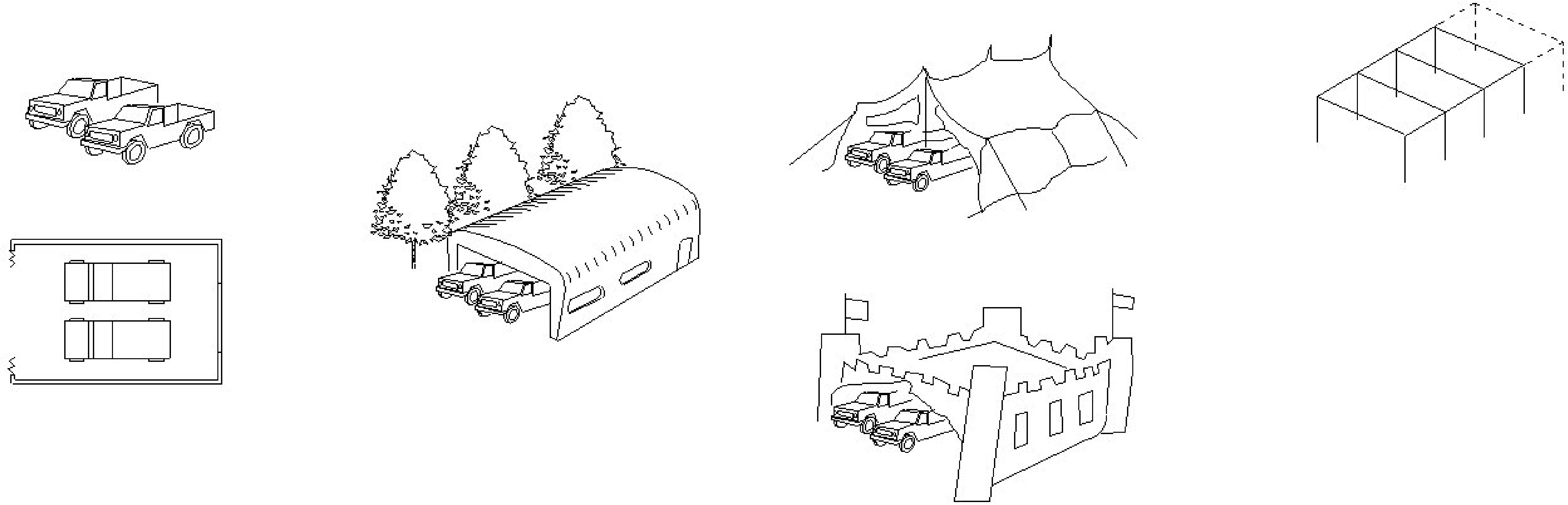


Figure 8 Initial concepts

3. HOW DOES THE DESIGNER DEVELOP HIS STRUCTURAL SYSTEM?

3.1 Pose an Initial Concept that may well Satisfy the Functions

These assumptions will be based on previous knowledge and understanding of actual constructions[8-13] or structural theory, see Figure 9 a, b, as well as the current availability of materials and skills. Initial consultations may be needed with suppliers and fabricators, e.g. for large quantities or special qualities of steel.

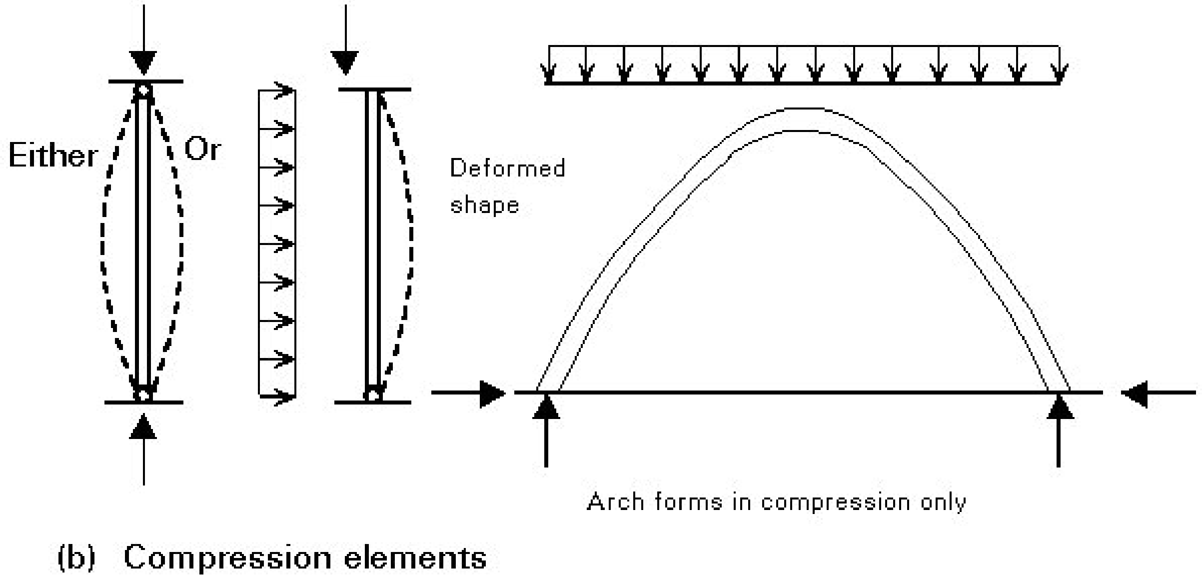


Figure 9a Load-carrying concepts

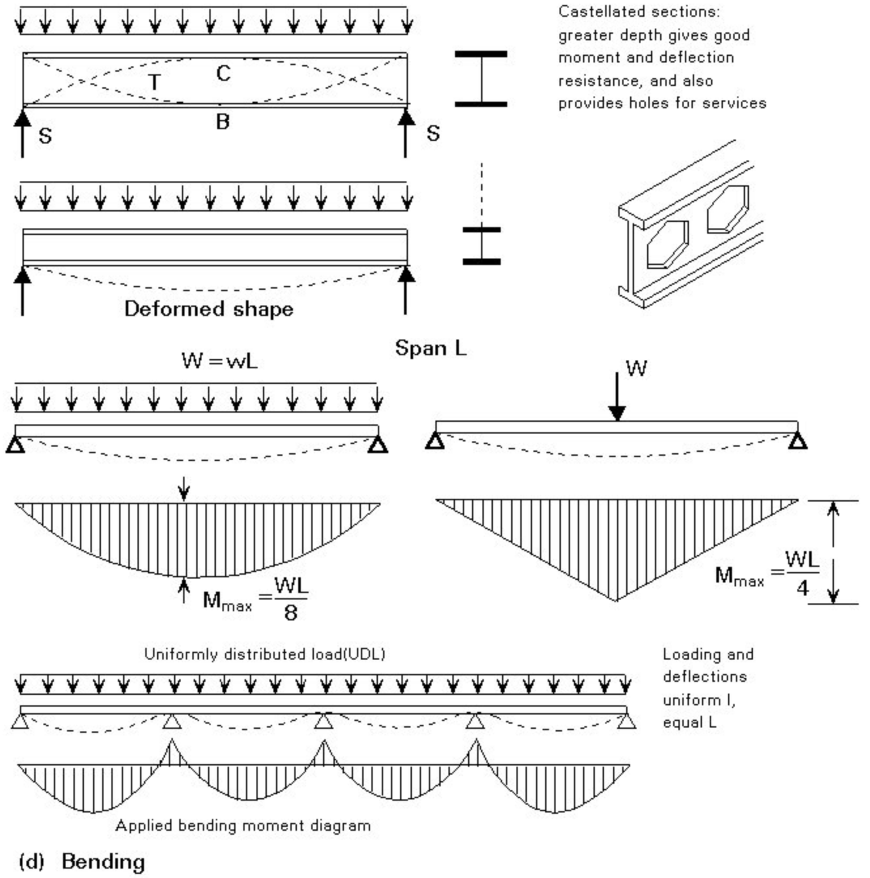


Figure 9b Load-carrying concepts

3. HOW DOES THE DESIGNER DEVELOP HIS STRUCTURAL SYSTEM?

3.1 Pose an Initial Concept that may well Satisfy the Functions

Steelwork, with its properties of strength, isotropy and stiffness, and its straight and compact linear elements, lends itself to 'Frame' systems, see Figure 9 c-e, which gather and transfer the major structural loads as directly as possible to the foundations, as a tree gathers loads from its leaves through branches and main trunk to the roots.

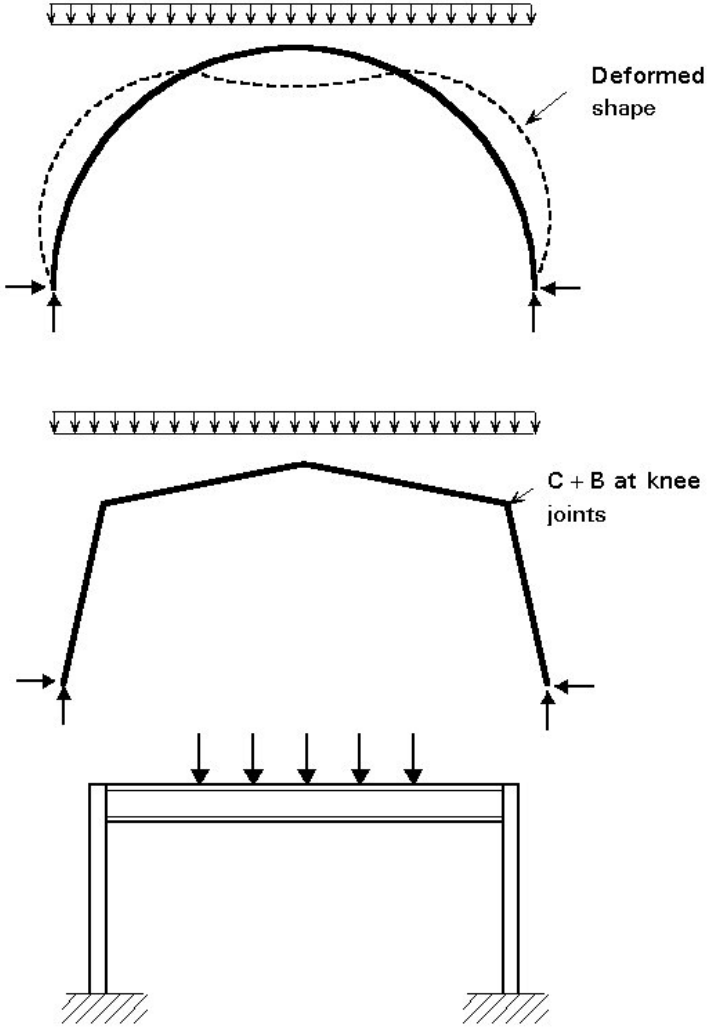


Figure 9c 2-D frames under vertical loading

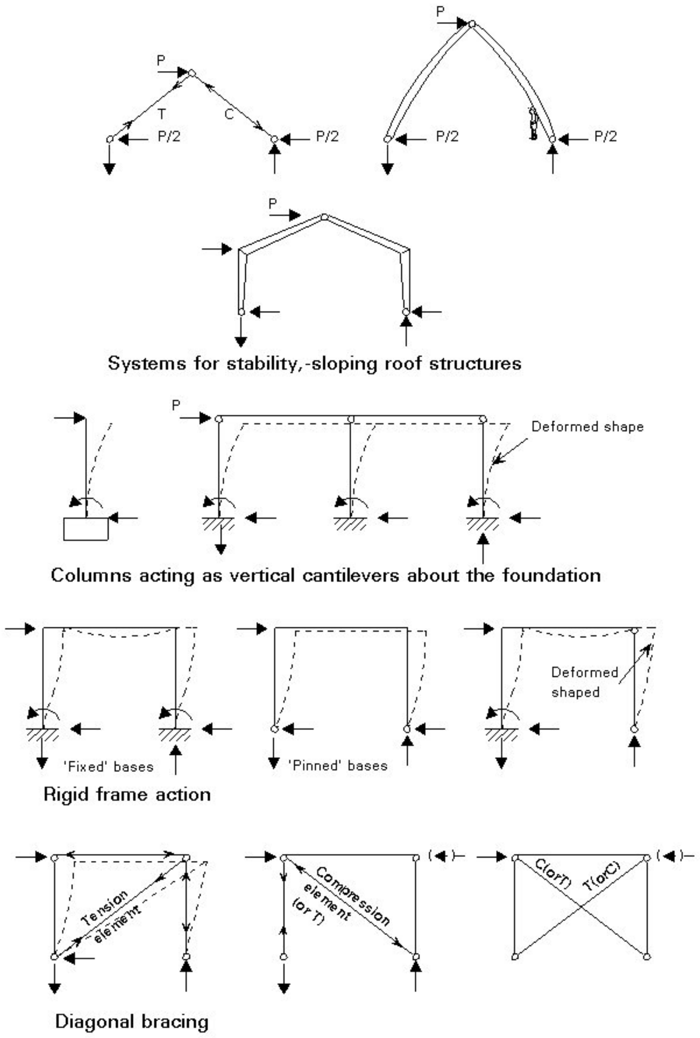


Figure 9d 2-D frames under horizontal loading

3. HOW DOES THE DESIGNER DEVELOP HIS STRUCTURAL SYSTEM?

3.1 Pose an Initial Concept that may well Satisfy the Functions

Next (and continuously) elucidate and test your ideas by making quick 3D sketches, or simple physical models, to explore the likely compatibility and aesthetic impact.

A range of stimulating evocative patterns viewed at different distances from, all around, and inside the buildings must be developed.

All these conditions should be satisfied, and especially for very large buildings for most of the time. Deficiencies may be made up in some people's minds if their social conditions change for the better or natural or changing phenomena occur, e.g. the rays of the setting sun suddenly give a completely different colour appearance or after sunset the interior lighting creates patterns previously unnoticed.

Form, colour, warmth and definition can be achieved with skilful use of steel, especially with "human scale" elements though repetition will soon induce boredom; but only as part of the complete sensory experience which must include elegant solutions to all aspects of the total building design.

It is very important that all principal specialists (architects, engineers for structure and environmental services) collaborate and communicate freely with each at this conceptual design phase.

Be prepared to modify the concept readily and work quickly. Timescale for an initial structural design concept: seconds/minutes. But hours will be needed for discussion and communication with others in researching an initial complete design idea.

3. HOW DOES THE DESIGNER DEVELOP HIS STRUCTURAL SYSTEM?

3.2 Recognise the Main Structural Systems and Ponder the Necessary Strength and Stiffness

Consider the applied live loads from roofs, floors or walls, and trace the 'load paths' through the integral 3D array of elements to the foundations, see Figure 10.

If the roof is assumed to be profiled steel decking, the rainwater should run to the sides, and a manufacturers' data table will indicate both the slope angle to be provided (4° - 6° minimum) and the secondary beam (purlin) spacing required, e.g. commonly 1,4m - 2,6m. The purlins must be supported, e.g. commonly 3m - 8m, by a sloped main beam or truss, usually spanning the shorter direction in plan, and supported by columns stabilised in three dimensions.

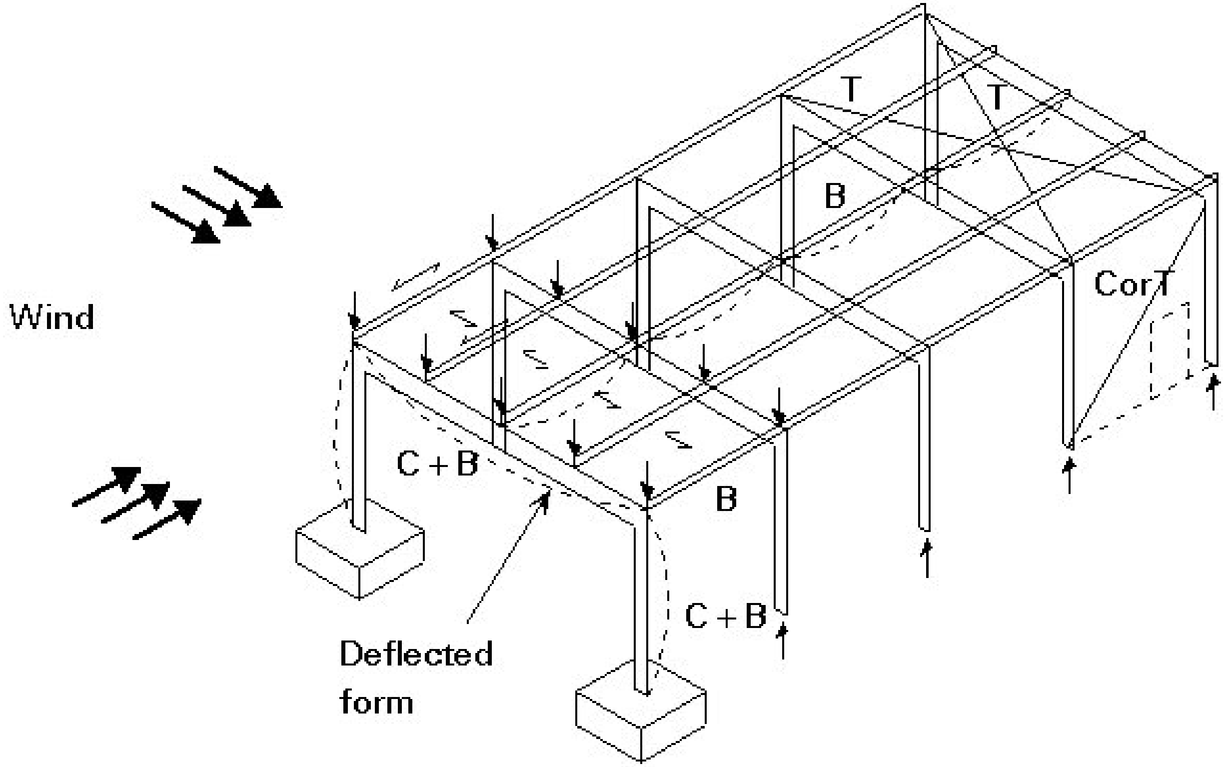


Figure 10 Main structural system

3. HOW DOES THE DESIGNER DEVELOP HIS STRUCTURAL SYSTEM?

3.2 Recognise the Main Structural Systems and Ponder the Necessary Strength and Stiffness

Wind loads on the longer side of the building can be resisted by cladding that spans directly to the main columns, or onto sidewall rails spanning between columns. The columns could resist overturning by:

- cross-bracing (in this case the large entry door would be impeded).
- or rigidly fixing the columns to the foundation bases ("linked cantilevers"); can the soil resist the extra overturning effect at the base?
- or rigidly fixing the tops of the columns to the main beams (creating 'portals') and giving smaller, cheaper "pin" base foundations.

Wind loads on the open short side of the building can be resisted by the opening door spanning top or bottom, or side to side. At the closed short side the wind loads can be resisted by cladding that either spans directly between secondary end wall columns, or onto rails to these columns.

At both ends of the building, longitudinal forces are likely to be induced at the tops of the columns. Trussed bracing can be introduced, usually at both ends of the roof plate, to transfer these loads to the tops of a column bay on the long side - which must then be braced to the ground.

Identify the prime force actions (compression C; tension T; bending B) in the elements and the likely forms of overall and element deflections for all applied loadings both separately and when combined.

3. HOW DOES THE DESIGNER DEVELOP HIS STRUCTURAL SYSTEM?

3.2 Recognise the Main Structural Systems and Ponder the Necessary Strength and Stiffness

It is always useful to have the elements drawn to an approximate scale, which can be done using manufacturers' data tables for decking and cladding, from observations of existing similar buildings, or using 'Rules of Thumb', e.g. the span/depth ratio for a simply-supported beam equals about 20 for uniform light roof loading, see Figure 11.

Indicative values		L/D	
Rolled steel sections		< 20	
Trusses: (one way span)	Heavy loading	12-15	Use higher values where rigid joints are used
	Medium loading	15-18	
	Light(roof) loading	18-21	
Space decks and grids:		15-45	Bolted-welded joints

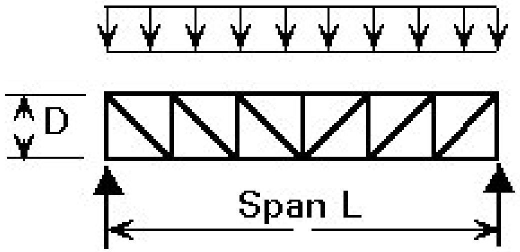


Figure 11 Rules of thumb for very preliminary estimates of size

3. HOW DOES THE DESIGNER DEVELOP HIS STRUCTURAL SYSTEM?

3.3 Assess Loads Accurately and Estimate Sizes of Main Elements

Establish the dead load of the construction and, with the live loads, calculate the following, see Figure 12:

- beam reactions and column loads (taking half the span to either side of an internal column).
- maximum bending moments, e.g. $wL^2/8$ for a simply supported beam, under uniform load.
- maximum shearing forces in beams.
- deflection values, e.g. $5/384\ wL^4/EI$ for a simply supported beam with uniform load.

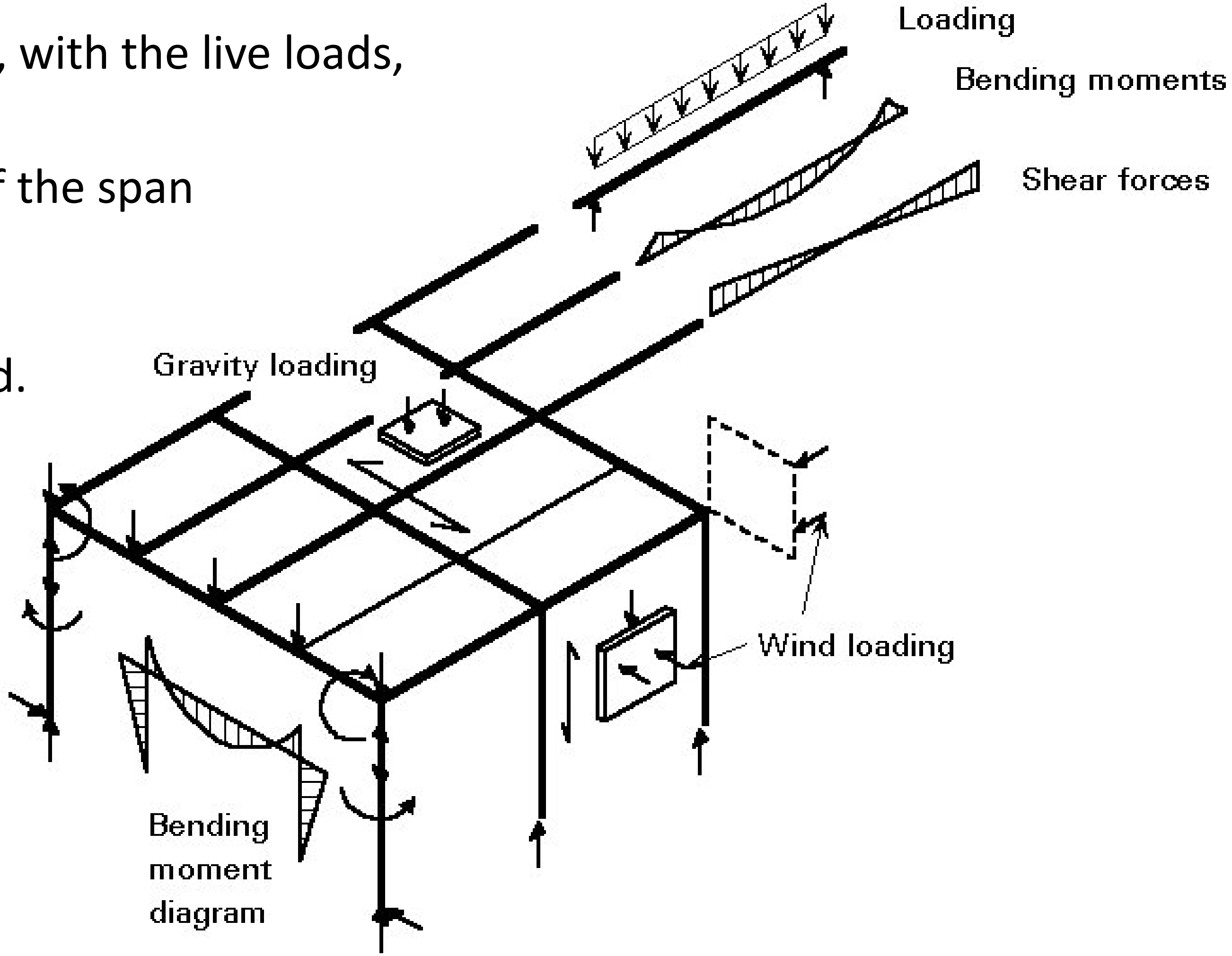


Figure 12 Approximate dimensioning of element sizes

3. HOW DOES THE DESIGNER DEVELOP HIS STRUCTURAL SYSTEM?

3.3 Assess Loads Accurately and Estimate Sizes of Main Elements

The size of columns carrying little moment can be estimated from Safe Load Tables by using a suitable effective length. Significant bending moments should be allowed for by a suitable increase, i.e. twice or more, in section modulus for the axis of bending.

Beam sizes should be estimated by checking bending strength and stiffness under limiting deflections. Structure/service duct or pipe integration may require beams to be as shallow as possible, or deeper and with holes in the web.

Likely jointing methods must be considered carefully: is the beam to be simply supported or fully continuous and what are the fabrication, erection and cost implications?

3. HOW DOES THE DESIGNER DEVELOP HIS STRUCTURAL SYSTEM?

3.4 Full Structural Analysis, using Estimated Element Sizes with Suitable Modelling of Joints, Related to Actual Details

Carry out a full structural analysis of the framework, either elastically or plastically. A computer may well be used, though some established 'hand' techniques will often prove adequate; the former is appropriate when accurate deflections are required, see Figure 13.

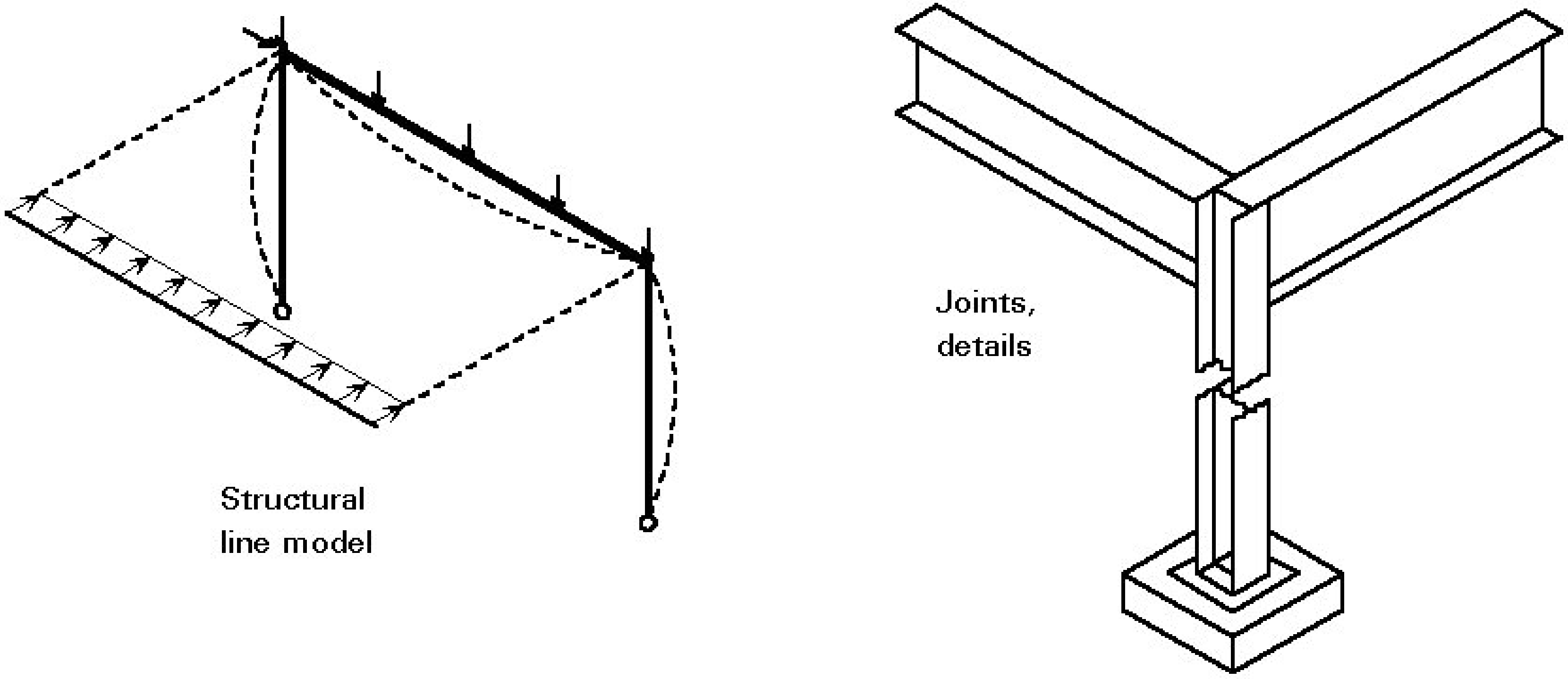


Figure 13 Final analysis and details

3. HOW DOES THE DESIGNER DEVELOP HIS STRUCTURAL SYSTEM?

3.4 Full Structural Analysis, using Estimated Element Sizes with Suitable Modelling of Joints, Related to Actual Details

For the analysis of statically indeterminate structures, an initial estimate of element stiffnesses (I) and joint rigidity must be determined by the third phase above, before it is possible to find the disposition of bending moments and deflections. If subsequent checking of the design of elements leads to significant changes in element stiffness, the analysis will have to be repeated. The role of the individual element flanges and web in resiting local forces within connections must also be considered very carefully when determining final element sizes. Excessive stiffening to light sections can be too expensive.

The analysis cannot be completed without careful structural integration and consideration of the compatibility of the entire construction system including its fabrication details.

Element joints will usually be prepared in the factory using welding, with bolts usually completing joints of large untransportable elements at site. Bracings, deckings and claddings will usually be fixed on site with bolts or self-tapping screws. It is important to remember that failures most frequently arise from poor jointing, details and their integration.

3. HOW DOES THE DESIGNER DEVELOP HIS STRUCTURAL SYSTEM?

3.5 Communicate Design Intentions through Drawings and Specifications

Prepare detail drawings and specifications for contractors' tenders, see Figure 14. Iteration of the design may again be necessary, due to variations in contractors' prices and/or preferred methods, e.g. welding equipment available, difficulties in handling steelwork in the fabricating shop or for transportation and erection. Changes and innovations in the design must be communicated and specified very carefully and explicitly.

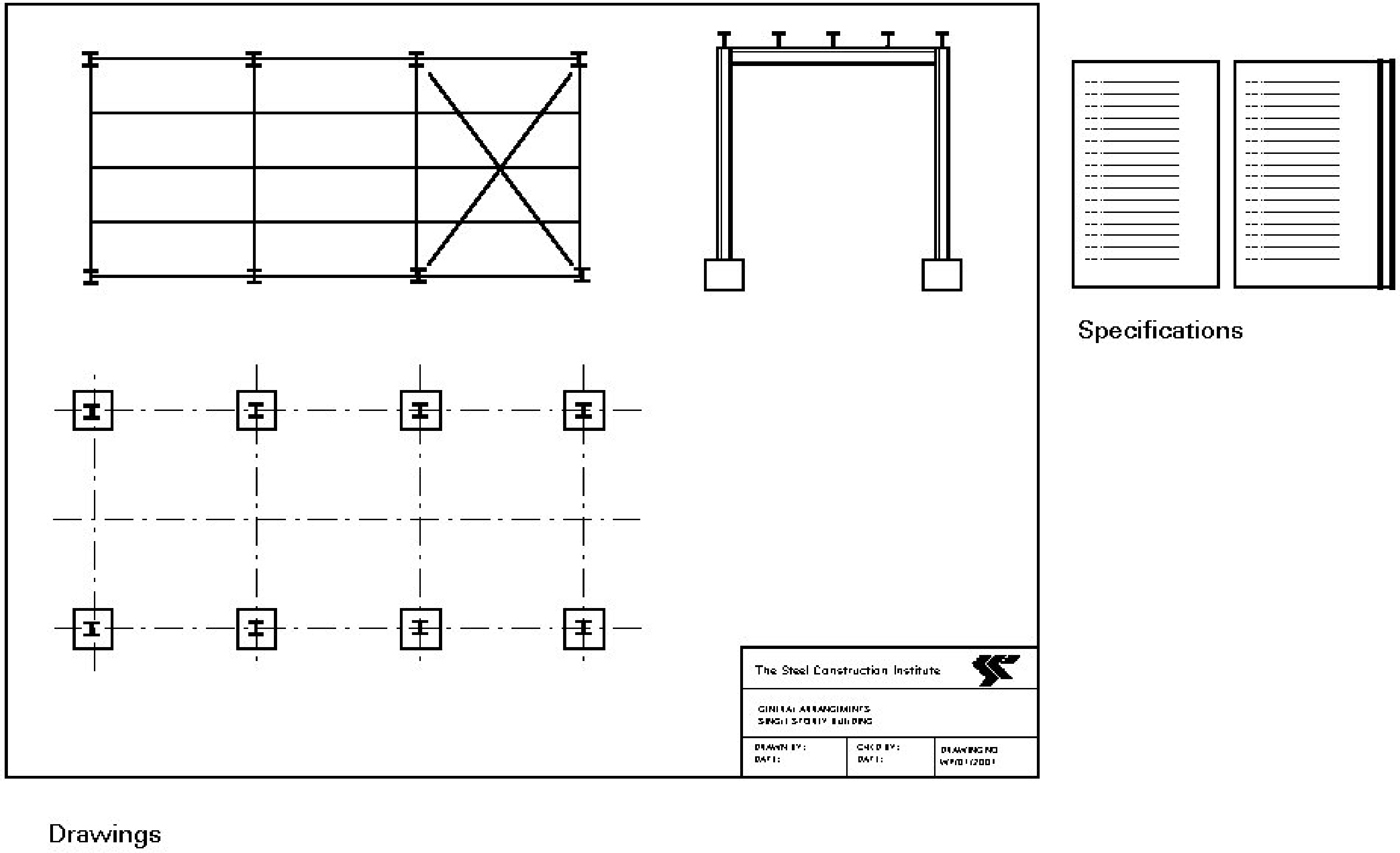


Figure 14 Communications

3. HOW DOES THE DESIGNER DEVELOP HIS STRUCTURAL SYSTEM?

3.6 Supervise the Execution Operation

Stability of the structure must be ensured at all stages of the execution, see Figure 15. High quality components and skilled erectors must be available at the right place and time, calling for very careful organisation. If 'all goes to plan' every piece will fit into the complete jigsaw.

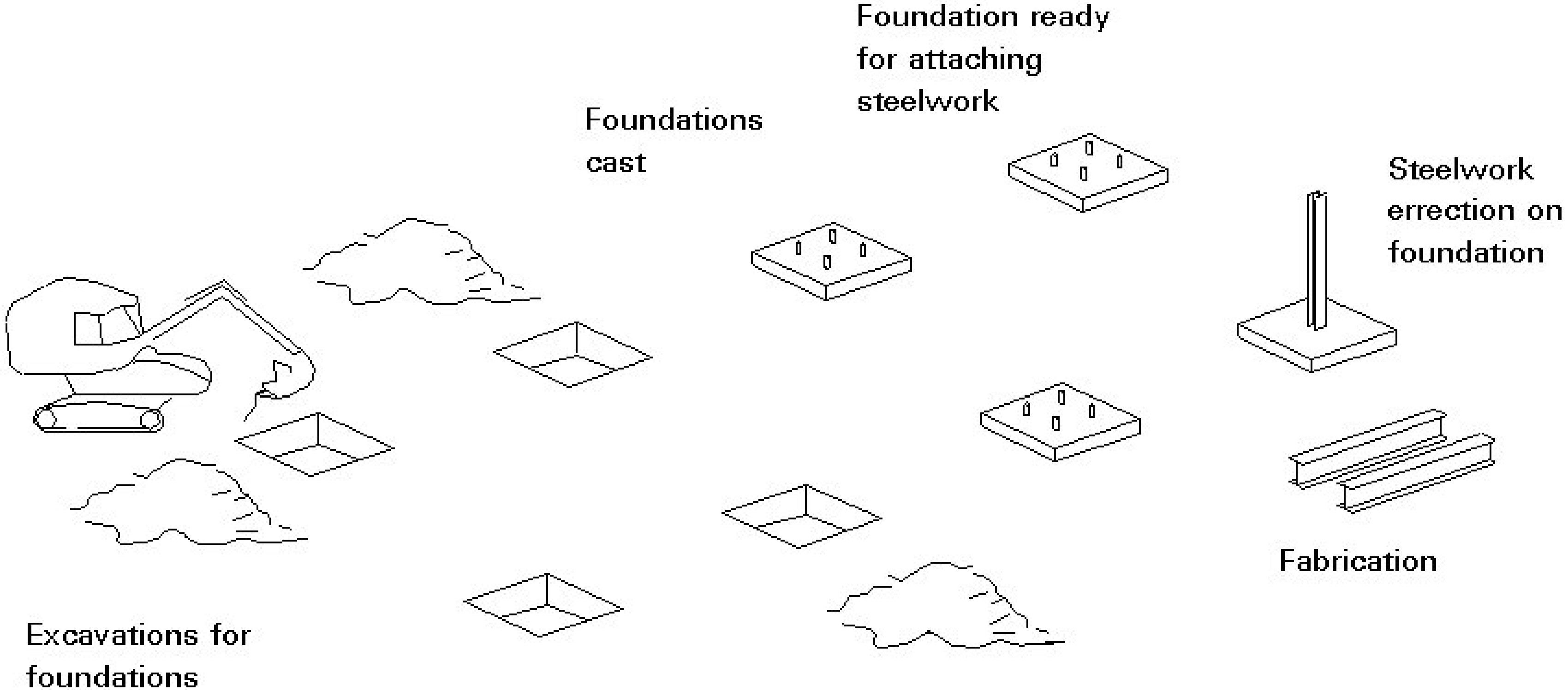


Figure 15 Execution

4. CONCLUDING SUMMARY

- This lecture introduces the challenge of creative design and suggests a holistic strategy for designing structural steelwork. It seeks to answer questions about what a designer is trying the achieve and how he can start putting pen to paper. It illustrates how a successful design is iterated, through qualitative ideas to quantitative verification and finally execution.
- Creative and imaginative design of structures is most challenging and fun - now try it and gain confidence for yourself. Do not be afraid of making mistakes. They will only be eliminated by repeating and exploring many other solutions. Make sure the design is right before it is built, using your own personal in-built checking mechanisms.

5. REFERENCES

[1] Gordon, J. E. 'The New Science of Strong Materials', Pelican.

[2] Gordon, J. E. 'Structures', Pelican.

[3] Gordon, J. E. 'The Science of Structures and Materials', Scientific American Library, 1988.

[4] Jones, J. C. 'Design Methods', Wiley 2nd Edition 1981.

A good overview of general design methods and techniques.

[5] Broadbent, G. H. 'Design in Architecture', Wiley, 1973.

Chapters 2, 13, 19 and 20 useful for designing buildings.

[6] De Bono, E. eg: 'Lateral Thinking' or 'Practical Thinking' or 'The Use of Lateral Thinking', Pelican.

[7] LeGood, J. P, 'Principles of Structural Steelwork for Architectural Students', SCI, 1983 (Amended 1990).

A general introduction and reference booklet to buildings for students.

[8] Francis, A. J, 'Introducing Structures, Pergamon, 1980.

A good overview text, especially Chapter 11 on Structural Design.

[9] Lin, T. Y. and Stotesbury, S. D, 'Structural Concepts and Systems for Architects and Engineers', Wiley, 1981.

Chapters 1-4 give a very simple and thoughtful approach to total overall structural design, especially for tallish buildings.

[10] Schodek, D. L, 'Structures', Prentice Hall, 1980.

Good clear introductory approach to structural understanding of simple concepts, also especially chapter 13 on structural grids and patterns for buildings.

[11] Otto, F, 'Nets in Nature and Technics', Institute of Light Weight Structures, University of Stuttgart, 1975.

Just one of Otto's excellent booklets which observe patterns in nature and make or suggest possible designed forms.

[12] Torroja, E, 'Philosophy of Structures', University of California Press, 1962.

Still a unique source book.

[13] Mainstone, R. J, 'Developments in Structural Form', Allen Lane, 1975.