Design and Performance of Tubular Steel Scaffolding

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ABSTRACT

Some structural design concepts of tubular steel scaffolding are presented herein. Factors that are considered in the design are loading condition, basic structural element, bracing, foundation and ancillary fittings. Emphasis is given to the use of modular frame scaffoldings according to the standards in some countries. Finally, the result of system performance test on a typical modular frame scaffolding system produced locally is presented. The results shows that the frame system has high buckling load capacity and complies with the standard specification.

INTRODUCTION

Scaffold falsework is defined as any temporary structure used to support a permanent structure during its erection and until it becomes self-supporting. The main emphasis in the construction of a scaffolding structure is to ensure stability of the structure and what it supports. If scaffolding collapse, it can result in death or injury.

In the United Kingdom the standards used for the construction of scaffolding is BS 1139:1982,1990 and 1991. Scopes covered in the standards are specifications for couplers and fittings for tubular scaffolding, specification for steel and aluminium tube and specification for prefabricated steel tube scaffolding. Other standards used for scaffolding are SS280:1984 (Singapore), JIS A8951:1985 (Japan) and AS/NZS 1576.3:1995 (Australia and New Zealand) which cover

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only prefabricated tubular steel scaffolding systems. In Malaysia, the standard for scaffolding has been drafted by a committee set up under The Standard Institute of Research and Industries Malaysia (SIRIM).

In the development of any scaffolding systems, the overall and local structural behaviour of the constructed scaffolding is to be analysed. For tubular steel scaffolding, the design is based on standard steel design guide such as BS 5950: The Use of Structural Steel in Building.

The general concept of scaffolding design is presented herein. Prefabricated scaffolding systems have been widely used in Malaysia therefore, a large proportion of the new standard had been based on version of the previous standard. In the process of developing the new standard, tests on mechanical strength of each part have been carried out in SIRIM. The structural behaviour of the erected scaffolding has been carried out in the structures laboratory, Universiti Teknologi Malaysia. The result of the test is presented in this paper.

FORMS OF SCAFFOLDING

When considering the various structural forms employed in the design of a scaffold, it is convenient to subdivide scaffolds into two types – support (falsework) and access:

Support – one of the most common requirements is to provide an elevated platform capable of supporting a specified load over a specified area (Figure 1a).
Access – for this form of scaffold there are three main design approaches:

i) An independent self-supporting structure erected adjacent to the permanent structure, and usually tied to it for lateral stability (Figure 1b)

ii) Putlog scaffold which rest partly on the permanent structure and obtains essential lateral stability from it (Figure 1c)

iii) Cantilever scaffold which bears entirely on and cantilevers, hangs or spans from the permanent structures.

DESIGN PRINCIPLES

The principles describe below are applicable to all tube and fittings scaffold structures and should be followed by the designer with respect to any particular case.

Loading

Loads on scaffolds should be calculated with as much care as for permanent structures because, although they may be applied for relatively short periods, their magnitude is often very great compared to its self weight. Types of load to be considered are:

1) Steadily applied loads - scaffold self-weight, dead load of permanent structures, equivalent unit load intensity for access and working load, wind load, and thermal loads.
2) Dynamic load (impact, surge, vibration), pouring of wet concrete, movement of plant and vehicles.

The determination of these loads is a matter of general engineering design procedure. According to BS 1139: Part 5: 1990: Metal Scaffolding, equivalent uniformly distributed load is between 0.75 kN/m^2 for Class 1 to 6.0 kN/m^2 for Class 6. For operational work (brickwall, plastering, etc.) which is of Class 4 or 5, the equivalent uniformly distributed load dl is in the range of 3.0 kN/m^2. An example of this load is due to the weight of 1 man, mortar and 200 bricks.

The load due to wind is converted into a pressure acting on the effective area of the scaffold which is defined as the projected area of the scaffold. In BS 1139, the maximum design wind pressure is 770 N/m^2 and the working wind pressure is 200 N/m^2. For the maximum design wind pressure, the wind pressure per unit length acting on a 48.4 mm diameter tubular pipe can be taken as 37.0 N/m.

Basic structural element

Several types of scaffold tube are used and may take the form of straight lengths, which are joined together by couplers, or may be component members joined together by patented attachments. Typical types of swivels are shown in Figure 2. The main material in use is mild steel and the general tube specification regarding dimensions and quality may be found in BS 1775: Steel tubes for mechanical, structural and general engineering purposes and BS 1139: Section 1.1: 1990: Specification for steel tubes. Normally it is specified that the yield stress should be greater than 235 N/mm^2.

The safe strut loads can be based on the Perry-Robertson formula as used in BS 5950: The Use of Structural Steel in Building: Part 1, which is simplified in Table 27 of the standard. A factor of safety 2.0 is used to give the allowable axial load on struts. For 48.4 mm outer diameter and 4.06 mm thickness tubular steel, the safe strut load for 1.8 m effective length is equal to 36.5 kN, assuming grade 43 mild steel with Modulus Yong, E=206 kN/mm^2 .

For the safe load calculation on horizontal tube, reference can be made to Clause 4.2 in BS 5950. For the 48.4 mm nominal diameter tube, the safe central point load for a tube used as ledger or transom of 1.2 m length is 3.6 kN. However, excessive deflections could result from these loads on longer spans, therefore the maximum safe load should be checked with the maximum limit of deflection at mid-span of simply supported tubes.

Nodes

Where a number of tubes converge at a node point, the degree of eccentricity should be minimised in order to avoid excessive eccentricity and bending in the tube. For example, for tube A in Figure 3, in X and Y axes,

$$M_{xx} = 7.07 \sin 45^{\circ} \times 2 \times 75 - (5 \times 75) = 375 \text{ kNm}$$
$$M_{yy} = 7.07 \cos 45^{\circ} \times 2 \times 75 = 750 \text{ kNm}$$

Maximum bending moment $= (M_{xx}^2 + M_{yy}^2)^{1/2} = 840$ kNm

It is slightly greater the moment resistance of normal tube with 48.4 mm diameter, i.e. 810 kNm. This simple analysis shows that with slightly greater eccentricity, the transverse node tube could be overstressed.

Basic structural form

Most scaffold structures are three dimension space frames with partial continuity at nodes of unknown characteristic. For practical design purposes, most scaffold structures may be analysed as two-dimensional pin-jointed frames, but only taking account of bending moments in members loaded as beams and due to eccentric load at the couplers. There are two basic structural forms to be designed.

i) Fully braced space frame with non-parallel members and loads acting in any direction (Figure 4a). This module is fully statically indeterminate and all members may be loaded.
ii) Partially braced rectangular lattice where loads are acting on one directional only, and are the most commonly used (Figure 4b). Only few members are loaded and the remainder provides nominal stabilising forces against lateral instability. Only alternate panels are cross-braced.

Diagonal bracing

In the case of multi-directional forces acting on a space frame, the diagonal member forces can be calculated. But under unidirectional loading, the magnitude of the forces in that bracing is often made arbitrarily by way of justification. The 1974 Interim Report of the Bragg Committee suggests that the force in the diagonal member is obtained from the relationship between the brace force, the strut load, the brace inclination and the strut deviation from true. The strut deviation is reasonably assumed as 1.5°. In another simple approach, a lateral restraint force is assumed as 2.5 percent of the force in the strut. The brace force F would become $(P/40) \sec \alpha$ where P is the strut load and α is the angle of the diagonal member. This gives $F = P/28$ for $\alpha = 45°$. If the brace strength F is 6.0 kN, therefore $P = 28 \times 6 = 168$ kN. However, one brace is usually sufficiently strong to stabilise a number of struts. This means that if the strut load is 30 kN each, one diagonal member (see Figure 5) can brace five struts.

Bracing for side thrust

Figure 6 shows a typical load condition for a free standing rectangular lattice scaffold braced to resist side thrust such as could be caused by wind pressure. In order to avoid too high a force build-up, it may be necessary to add another bracing as shown. (Figure 6b).

Foundation

The principles of normal foundation engineering and soil mechanics must applied to scaffolds as for permanent structures, but there are certain foundation design problems peculiar to scaffolding which should be mentioned here:

1) Founding on fill - ground as low as 25 kN/m^2 should be used to avoid settlement at the base.
2) Use of timber base or concrete blinding or both is preferred to ensure good overall bearing
3) Tension foundation - it is sometimes necessary to provide resistance to incline or vertical uplift.
4) Foot ties - Feet of standards should be interconnected by tubes in two orthogonal directions to prevent lateral movement.

Fittings and ancillary

Base:
The purpose of the base fitting (Figure 7a) is to transmit axial thrust from the end of a tube onto a bearing surface and at the same time spread the thrust over an area such that the contact pressure is reduced considerably. Adjustable base is used where a scaffold bears onto an uneven or sloping site. A safe working load of 65 kN is normally required by standards. For this requirement, the threads must be smooth acting and robust, usually either Whitworth or Acme.

Forkhead:
The purpose of the forkhead (Figure 7b) is to transmit load onto the top of a scaffold tube standard. The maximum load, W, may be calculated for a strut of diameter d and effective length $2L$ subject to axial load W and bending moment We where e is an eccentricity due to a possible angular and positional misalignment.

Hop-up bracket:
The bracket is fixed to the scaffold in order to provide an additional platform support (Figure 7c). The main point to check when using the ancillary is that it does not, owing to its eccentric loading, overstress the standard by the action of the horizontal force component at its bottom connection.

Example on loading calculation

It is required to provide a steel independent access scaffold for purpose of construction of a multi-storey 124 m high office building (Figure 8). The height of one storey is 3 meter and the scaffold lift heights required are 2 m. The top six lifts are required for column and beam shutter erection and stripping, concreting and cladding operations. It is required to check the total load transferred to each standard if there are three standards per group at the bottom lifts. Maximum load per standard group may be calculated as follows:

$$W = W_T(N_L + N_D)\left[1.5H + nH + \frac{2}{3}D + B\right] + 3W_C(N_L + N_D)$$
$$+ 0.75\, w_D\, B\, D\, N_D + n\, N_L\, W_C$$

where,

W_T	=	unit weight of tube	=	4.3 kg/m
W_C	=	weight per coupler (average)	=	2 kg
H	=	lift height	=	2 m
B	=	c/c of standard longitudinally	=	2.1 m

D	=	c/c of standard transversely	=	1.2 m
N_L	=	number of lifts = 124/2	=	62
N_D	=	number of loaded lifts	=	6
W_D	=	uniformly distributed deck load	=	220 kg/m^2
n	=	number of standards per standard group		
W	=	4.3(62+6)[(1.5+3)2 + 0.67(1.2) + 2.1] + 3(2)(62+6)		
		+ 0.75(220 x 2.1 x 1.2 x 6) + 62 x 2 x 3		
	=	6755 kg.		

The load per standard is therefore 6755/3 = 2251 kg. This load is to be checked with the maximum safe strut load of the tube. Further checks can be carried out at higher loads to ascertain where the triple standard can be reduced to double and so on.

MODULAR TUBULAR SCAFFOLD SYSTEMS

There is a multitude of systems whereby various metal (steel or aluminum alloy) components are linked together , usually without the aid of usual couplers, to provide a structure which would replace a normal tube and fittings scaffold. These systems offer a direct requirement to the tube and fittings scaffold.
Because in general the normal tube coupler is omitted, considerable erection time may be saved which is an advantage for short life scaffolds. Modular components fit together simply and quickly and provided the base is correctly lined and leveled, the scaffold needs little further setting out or plumbing because of its modular nature.

Frame and brace system (Fig. 9) is the most commonly available system consists of two basic components:

a) The welded tubular frame which fits via spigots one onto another and which may be obtained in a large variety of shapes and sizes. Each unit consists of a pair of standards or vertical tubes of about 48 mm diameter (2 in. nominal) mild steel and thickness of between 2 to 4 mm, connected by a horizontal member and stiffened by reinforcement members to make it a rigid frame.
b) The cross brace which usually consists of two length of light angle or tube pivoted at mid length and provided with holes at the ends which fit over studs with quick-locking devices projecting from the legs of the frames.

Standard specification of steel frame scaffolding

The national standard specification for steel frame scaffolding is being drafted by the Standard Writing Organisation (SWO) technical committee of the Malaysian Iron and Steel Industry Federation (MISIF) for the Standard Industries and Research Institute of Malaysia (SIRIM). The committee is represented by government departments, universities and steel fabricators. In preparing the standard, the technical committee appreciated the fact that there are various designs of frame scaffolding. Taking into consideration the conditions existing in Malaysia, reference was made to Singapore Standard for Frame Scaffolding, SS280-1984 which adopt frame and brace system.

Dimension and performance requirement of frame scaffold components is given in the standard as shown in Table 1. The term used is illustrated in Figure 10, which is not regarded as part of the specification. The frame scaffolding and its components shall meet the performance requirement of the table when tested in accordance with the standard. The dimension of the frame and bracing member are specified in a way so that it capable of supporting load of 40 m high scaffolding frame with one lift loaded with 220 kN/m^2.

Table 1 Dimensional and performance requirements of frame scaffolding

Member	Constitutional part	Dimensions (mm)	Load test requirement
Vertical frame	Standard and horizontal member	42.7 x 2.5	Vertical deflection under 9.81 kN = 10 mm max.
	Reinforcement member	27.2 x 2.0	Compressive strength of standard = 73 kN min. for
	Cross brace pin	14.0	for 1.8 m and 68 kN for higher than 1.8 m.height.
Cross brace	Brace member	21.7 x 2.0	Compressive strength = 7.3 kN minimum
	Hinge pin	7.5	Strength of hinge pin = 5.88 kN minimum
Horizontal frame	Tube member	42.7 x 2.5	Vertical deflection = 10 mm max.
	Transverse member	34.0 x 2.3	Bending strength = 4.9 kN min.
	Grip fitting or hook	8.0	
Catwalk	Catwalk member	500 x 1.2	Vertical deflection = 10 mm max. Bending strength = (width in mm x 0.0108) kN min.
	Clamp or hook	8.0	Shearing strength =(width in mm x 0.0353) kN min.
Base plate	Shank	35	Compressive strength = 59.8 kN min.
	Baseplate	140 x 140	
Bracket			Under strength test, slip = 10 mm max. Strength = 39.2 kN (fixed type), 22.76kN (adj.type)
Armloack			Elongation = 2 mm max. Strength = 5.88 kN min.
Wall tie			Tensile and compressive strength = 8.883 kN min

PERFORMANCE TEST OF STEEL FRAME SCAFFOLDING

System performance tests of steel frame scaffoldings have been conducted in the Heavy Structures Laboratory, Faculty of Civil Engineering, Universiti Teknologi Malaysia. The tests were conducted on two scaffolding frame samples, each of Huatraco Sdn Bhd and Jashin Sdn Bhd.

Three bay by three lift frame scaffolding for the test (Fig. 11) is subject to a load which represents the weight of 24 lifts (to the height of 40 m) with one loaded lift. Bracings were provided to ensure that the loading jack which was secured at the top of the column through a pair of beam remained in its original position during load increment. There were six points for deflection measurement - each measured at mid-lift in longitudinal and transverse directions. Deflections of standards were measured by displacement transducers fixed on an independent stand.

Two tests have been conducted on each sample namely, stiffness test and strength test. In each test, load was increased at a rate of 1.0 kN per minute from zero to the maximum test load specified in the standard. The maximum load was then maintained for 15 minutes before unloading.

Dead load per-bay for 40 m high scaffolding (due to mainframe, coupling pin, catwalk, cross bracing, arm lock, steel net, and wall joint is 2007 kg, while the working load on one loaded lift is 220 x 1.218 x 1.83 = 490.4 kg. For the stiffness test, the test load is (2007 + 1.5 x 490.4) = 2743 kg. For the strength test, the test load is (2007 + 490.4) x 2 = 4995 kg. The load factors 1.5 and 2.0 are as specified in the standard.

For the stiffness test, the standard specifies that, the residual deflection upon unloading should not greater than 80% of the respective maximum deflection. For the strength test, it is specified that the residual deflection should not greater than 80% of the respective maximum deflection. In both tests, all the samples tested met the standard requirements.

Ultimate load test was then carried out on the sample. The ultimate load, i.e., when excessive buckling observed was around 75 kN. Figure 12 shows one of the scaffolding frame systems with the buckled vertical frame. The ultimate load capacity per individual frame is 80.0 kN as specified in the standard, which has been achieved in the test conducted by the Standard Industry and Research Institute of Malaysia (SIRIM). Since in this test, three frames were stacked one on each other and only connected by pin joint, it was expected that the ultimate buckling load would be much lower. However, the test results showed that the systems have high buckling load capacity. The strength is due to the stiffness of the joints and the cross bracing members.

CONCLUSIONS

Some basic considerations for the design of tubular scaffolding and tests on frame scaffolding have been presented. Although modular frame scaffolding system is more widely used in construction, the basic principles of design may be used as a reference such as in the design of timber scaffolding. Since the specification being developed by the standardisation authority is for frame and brace modular system, it is recommended that fabricators should produce this type of design. Tests on components and the assembled system have indicated complicity of typical specimens with the drafted standard.

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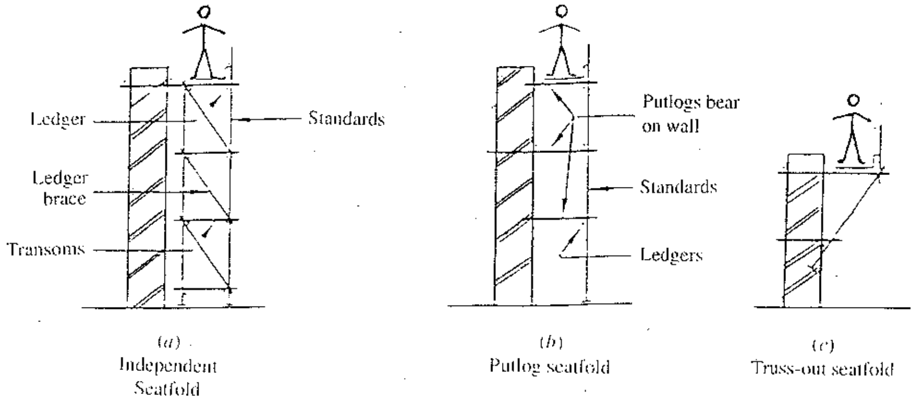


Figure 1. Basic access scaffolds

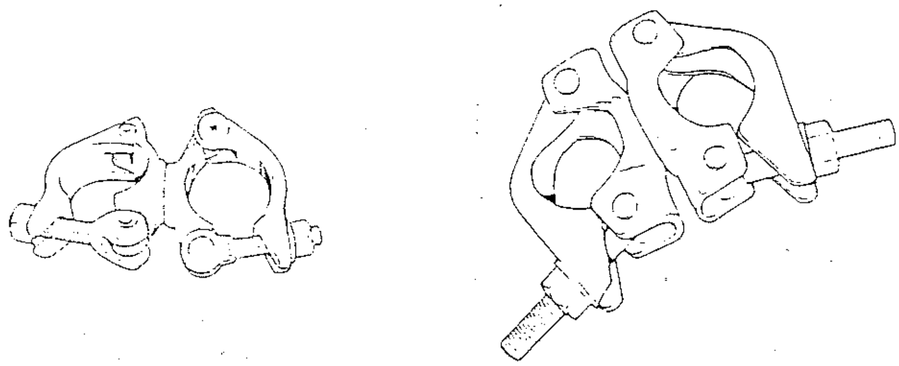


Figure 2. Typical swivel couplers

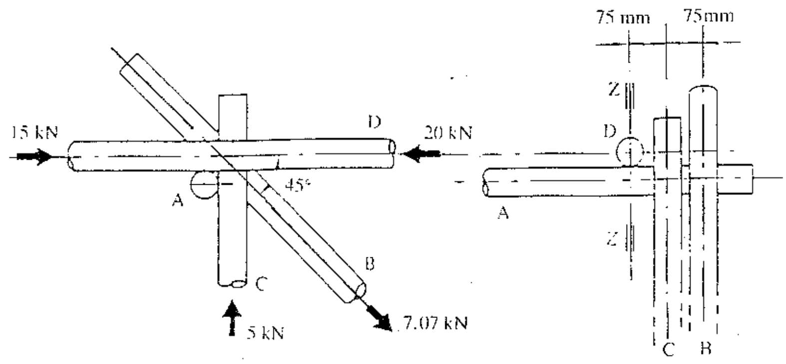
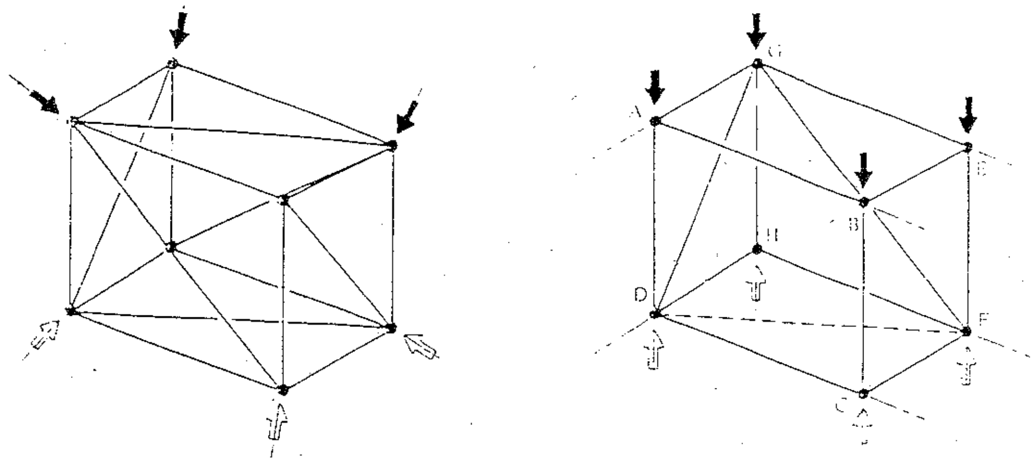


Figure 3. Eccentricity of tubes at a node point



(a) (b)

Figure 4. Two basic structural forms

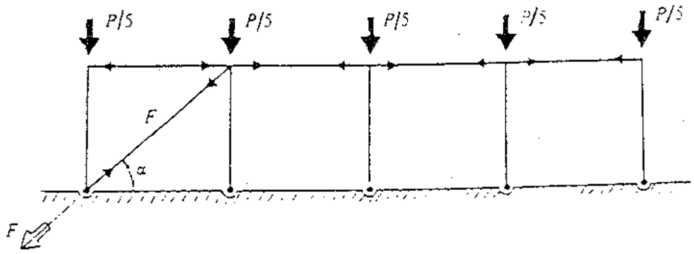


Figure 5. Brace forces

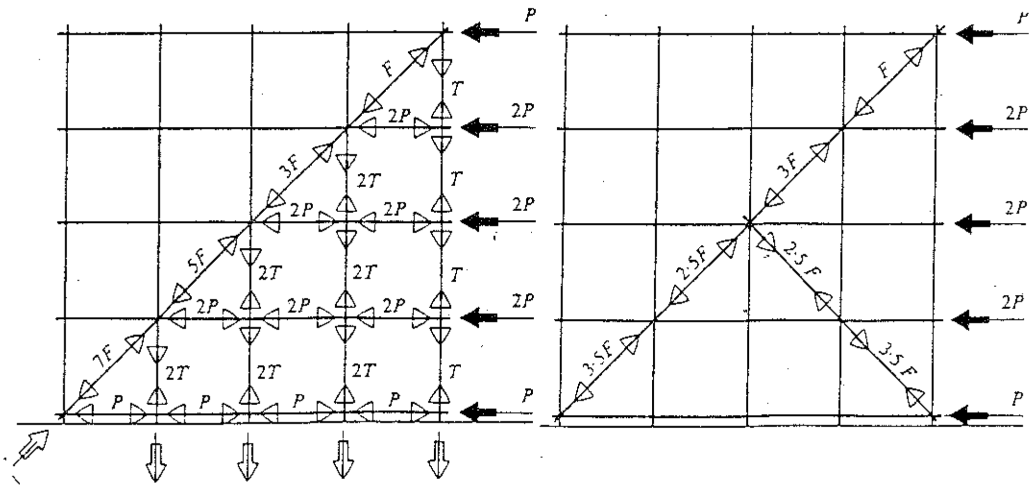
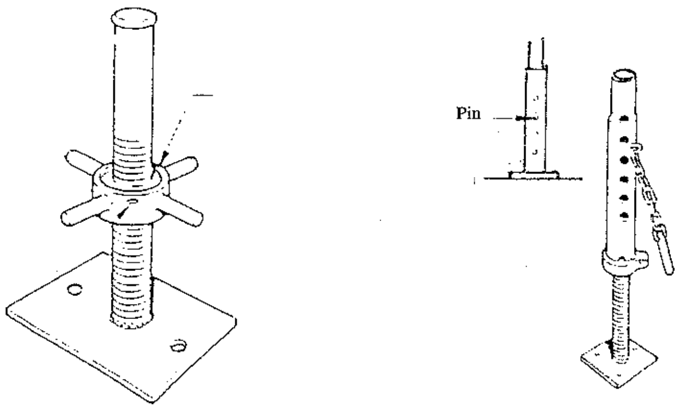
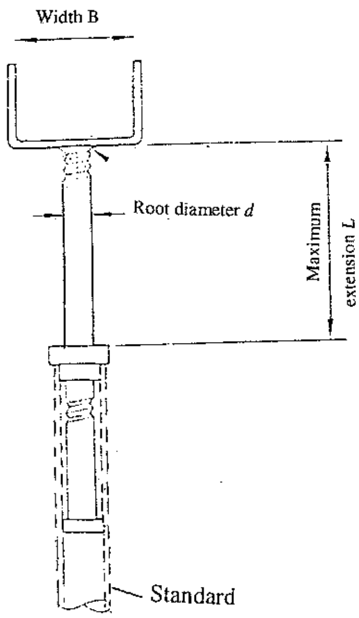


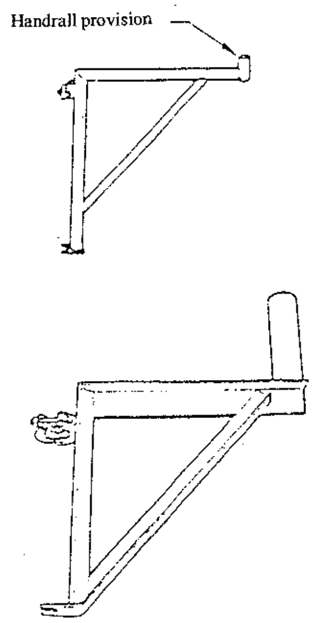
Figure 6. Forces in bracing due to side thrust



(a) Adjustable leg



(b) Forkhead



(c) Bracket

Figure 7. Fittings and ancillary

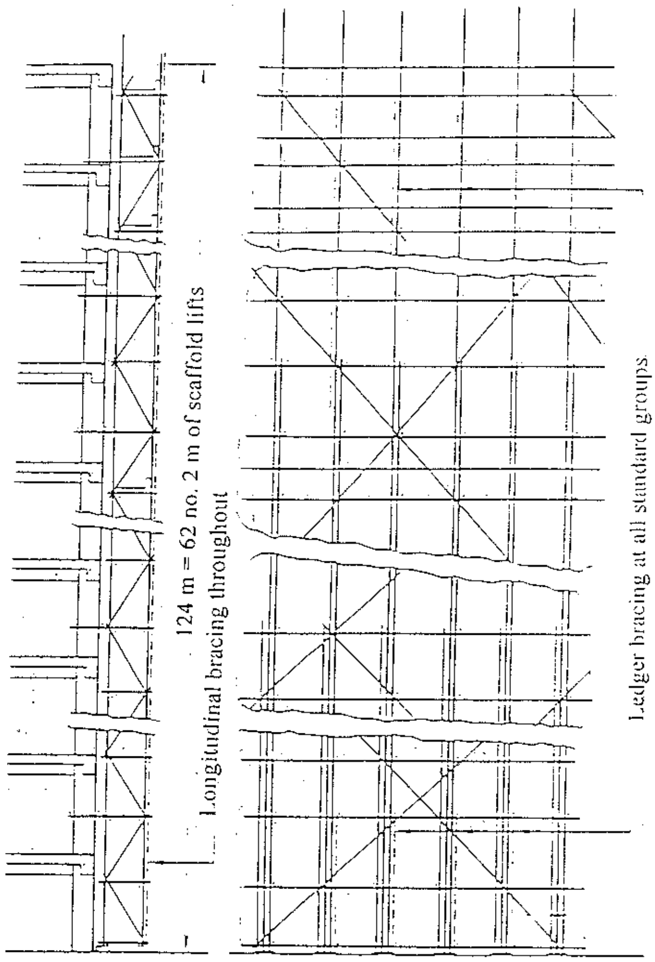


Figure 8. High scaffold design

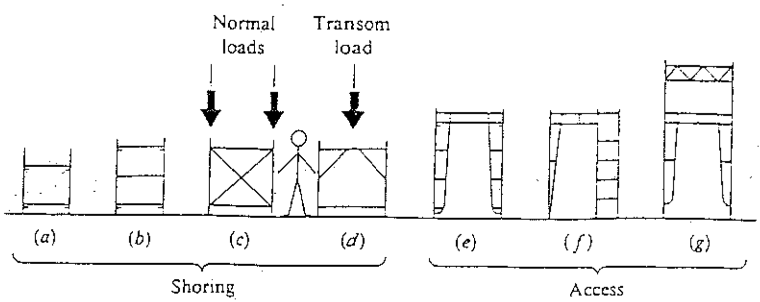


Figure 9. Typical braced frames

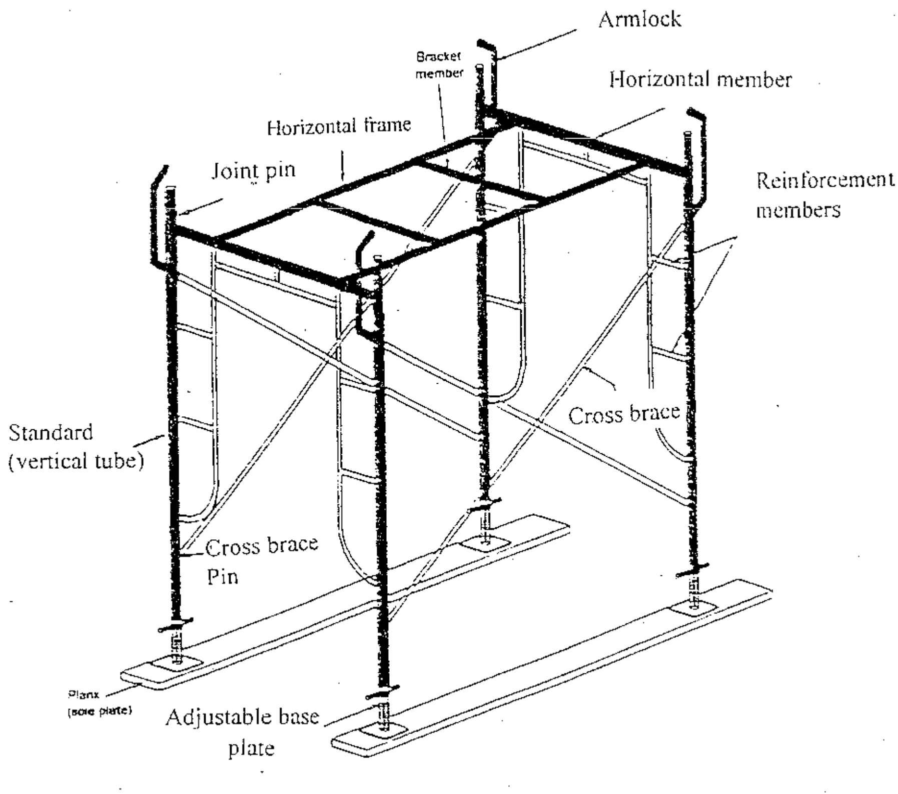


Figure 10. A framed scaffolding unit

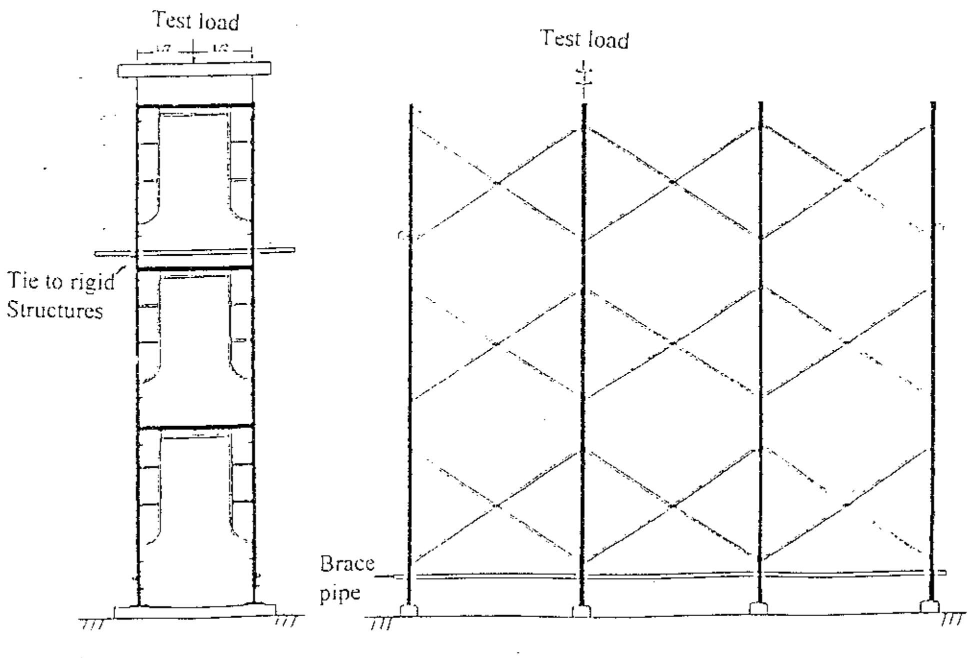


Figure 11 System performance test on framed scaffolding

Figure 12 The buckled vertical frame at ultimate failure