Beale, RG

Scaffold research – a review.

Beale, R (2014) Scaffold research – a review. *Journal of Constructional Steel Research*, 98 (1). pp. 188-200.

doi: 10.1016/j.jcsr.2014.01.016

Scaffold Research – a review

Robert G. Beale

Faculty of Technology, Design & Environment, Oxford Brookes University,
Wheatley campus, Wheatley, Oxfordshire, UK OX33 1HX.

Corresponding author: rgbeale@brookes.ac.uk

Abstract:

This paper reviews the research conducted throughout the last forty years into scaffold and falsework structures. Following a brief historical survey it describes the development of non-linear models and their correlation with test procedures. Recommendations for modelling connections are given. Vertical dead and imposed loads, wind and seismic loads are discussed. Finally the paper reviews research into collapses and shows that the majority of failures occur due to inadequate site supervision and poor design.

Key-words: scaffold; falsework; collapse; wind load; modelling

1. Introduction

The objective of this paper is to review and summarise research into scaffold structures over the last forty years and show the development of modelling procedures during this time. Prior to 1970 scaffolds were commonly analysed by hand calculations using effective lengths. The results of standard calculations were summarised in text books such as those by Brand [1] and Wilshere [2] and design codes and manufacturer load tables [3-6]. Previous shorter reviews have been conducted by Beale [7] in 2007 and Chandrangsu and Rasmussen [8] in 2009. André et al have conducted recent reviews and given design guidance for bridge falsework [9].

Failures of scaffold and falsework structures in the 1960s in the UK led to the Institution of Civil Engineers and the Concrete Society writing a report about formwork procedures [10] whilst the government set up an advisory committee into falsework which produced in 1975 the Bragg Report [11]. This report became the basis of the first version of BS 5975 [12]. At the same time research was commissioned by the UK Science Research Council into scaffold structures at Oxford University under Professor Lightfoot which was published in 1975 and 1977 [13-17].

This research showed that scaffold structures failed primarily by elastic instability. Harung et al [13] constructed model single storey tower scaffolds which were loaded by dead loads on the top. A stability-function [18] based finite element program was written to analyse the scaffolds. However, in the models all joints were either pinned or fixed and no eccentricity of either member or connection was included. The models failed by buckling and the theoretical models gave results between 10% and 15% higher than experiment. A model three storey scaffold failed with similar differences between experiment and theory. The conclusions drawn were that the effective lengths of the columns (called standards) should be taken to be larger than 1. In addition they concluded that for scaffolds containing spigots (connections with one section resting upon a second) in the standards that the spigot could be considered rigid. Later research shown below will show the inaccuracy of this conclusion for some scaffolds.

A major distinction in scaffold structures are those made from prefabricated components such as Cuplok [19, 20] or modular scaffolds such as the 'door-shaped' ones often used in the US and Asia [21] and scaffolds made from steel tubes (called tube-and-fitting scaffolds) [22] or bamboo [23]. Proverbs et al [24] compared French, German and UK practice and found that tube-and-fitting scaffolds predominantly dominated high-rise in-situ concrete formwork but that the UK also used proprietary scaffold systems, the Germans used specially designed solutions and the French used a variety of different systems. A comparison of timber and metal scaffold systems is given by Yip and Poon [25] where they showed that if formwork was not able to be reused that timber was often more economical.

This paper will review the methods of determining connection and section properties, followed by reviewing scaffold and falsework models, finally reviewing scaffold and falsework safety.

2. Connection behaviour and section properties

2.1 Tube and fitting scaffolds

Tube-and-fitting scaffolds are normally made from steel tubes connected by couplers. The common couplers are called putlog, right-angled and swivel and are shown in Fig. 1. The tubes are made from mild steel (typically circular tubes diameter 48.3 mm, thickness 4 mm, yield strength 235 N/mm^2). Test results on tubes were reported by Allen and Sholz [26] who proposed a column curve. Hŭbner and Saal [27] found that the buckling curve in BS EN1993-1-1 [28] is conservative and have recommended an alternative curve. Brand [29] proved out that effective lengths of scaffold tubes were not solely dependent on the spacing between horizontal members (called ledgers and transoms) but were also dependent on ledger flexibility. Lindner and Hamaekers [30] investigated screwed connections which are used for base jacks in tubular scaffolds and derived modified section and material properties for these tubes. Mansell and Angelidis [31] described a procedure to load scaffold assemblies which are prone to sway and hence standard test jack arrangements can put eccentric loads into the structure causing premature failure.

Lightfoot and Bhula [16, 17] determined the elastic properties of tube-and-fitting couplers by idealising the connection as an elastic beam with three translational and three rotational stiffnesses at each end. An experimental rig was developed to determine the six stiffnesses. The resulting stiffness matrix was then incorporated into Harung's program [14, 15]. The papers showed that the difference between modelling using an exact beam model with eccentric springs and a simplified approximate model using a single six degree of freedom spring was negligible. The researchers showed that the translational stiffnesses of couplers could be taken to be infinite and hence only the three rotational stiffnesses need to be determined. In tube-and-fitting scaffolds there is an eccentricity of approximately 50mm between two tubes. The effect of this eccentricity was shown to be small. This was verified by Milojkovic et al [32].

In the development of Euronorms for scaffolds Volkel and Zimmerman [33] and Hertle [34] conducted investigations into the properties of couplers and their effects on analysis. Abdel-Jaber et al [35] undertook an extensive series of test on putlog and right-angled connectors using the cantilever test according to BS EN12810 [36] and BS EN 12811 [37] to determine the rotational strength of both new and used couplers. They found that there was little difference between new and used couplers but recommended minor changes to the Euronorms to remove some ambiguities in the codes. They also recommended that putlog couplers and Type A right-angled couplers be added be added into BS EN 74 [38] which currently only has values for Type B right-angled couplers. Typical moment-rotation curves are given in Fig. 2. From the figures it can be noticed that both types of connector exhibit looseness which is normally ignored in analyses but which can be shown to have significant effects [39].

Son and Park [40] surveyed the spacing of tubes in scaffolds in domestic construction and found that normally they were placed within the range of allowed standard spacing. However, torques applied to coupler fastenings varied considerably and often were less than 65% of the expected torque.

2.2 Proprietary scaffolds

As part of the process for the development of European codes for scaffolding experiments were undertaken at Oxford Brookes University (formerly Oxford Polytechnic) [41, 42] and Stuttgart University [33, 43] into the properties of proprietary scaffolds. The properties of the connections about an axis at right angles to the standard (column member) were obtained by the cantilever test. However, rotational characteristics about axes parallel to standards were obtained by using mini-frames as shown in Fig. 3. Fig. 4 shows a typical load-deflection curve. The large looseness obtained in the connection under cyclic loading is clearly visible. The relationship between load-deflection curve and moment-rotation curve for the case shown in Fig 3(a) is

$$\frac{M}{\theta} = \frac{WL^2}{8\Delta} \tag{1}$$

where M / θ is the moment-rotation stiffness, W the applied load, L the ledger span and Δ the measured deflection.

In order to obtain data for reliability analyses Chandrangsu under the supervision of Rasmussen undertook tests on Cuplok scaffolds with varying numbers of horizontal members (from 1-4) connected to the vertical standard using cantilever tests [44-46]. They produced tri-linear moment-rotation curves. A criticism of these curves is that the tests were conducted to failure without any cycling and hence looseness of connection was not determined. As will be seen later, looseness can yield significantly different results. In part of a continuing research project into bridge falsework reliability André et al [47, 48] have repeated the tests cycling the loads at early parts of the tests with similar results for loading but also determining some unloading curves. In addition in [48] they reported on tests on fork-heads and baseplates and produced reliability results.

Tests have not been reported on individual components of modular scaffolds but whole systems have been tested and will be described below.

2.3 Bamboo scaffolds

Bamboo scaffolds are commonly used in Hong Kong and East Asia due to low costs associated with bamboo [23, 49, 50]. The material properties of bamboo were reported for two structural bamboos – Kao Jue and Mao Jue by Chan and Xian [51], by Chung and Yu [52, 53] and Lu et al [54].

The connections between horizontal and vertical members are taken as simply-supported and calculations involving structural bamboo are given in Yu et al [55, 56], Chung et al [57, 587], Chan and Chung [59] and Janssen [60].

2.4 Extendable Props

The design of extendible props in Europe is governed by BS EN 1065 [61]. This standard was based on the German standard DIN 4422 [62]. An exact solution of the differential equations governing the theoretical model is found in Chapter 8 of Feng's PhD thesis [63]. Salvadori [64] also derived a theoretical solution to the equations and developed a commercial program. A research project was undertaken at the Portuguese National Laboratory for Civil Engineering (LNEC) by André et al [65, 66] where the props were modelled numerically and the theoretical results compared with experiments on the capacity of the props, especially when used on sites.

Peng et al [67] experimentally investigated single layer single layer shore systems and showed that props in excess of 3.96 m failed by buckling and below that by connecting lock failure. They also showed that attaching a wooden shore above the top of the prop reduced the overall capacity of the system.

3. Scaffold Modelling and tests

3.1 Tube-and-fitting models

The UK design codes BS 5973 [68] and BS5975 [12] used effective lengths to determine scaffold designs. However, effective lengths for the standards used in scaffolds are difficult to determine as the horizontal ledgers and transoms elastically restrain columns at intermediate points. With the introduction of BS EN 12812 [69] and BS EN 12811 [37] the UK National Access and Scaffolding Confederation commissioned Oxford Brookes University to produce a new design guide so that scaffolds using tube-and-fitting scaffolds could be safely erected [70]. During the development of the design guide many computer models needed to be produced and analysed. Beale and Godley [22, 71-73] developed one and two dimensional models which were validated against full 3-D analyses. Fig. 5 and Fig. 6 give schematics of the two common scaffolds used to access the sides of buildings – a single-layer (called a putlog) scaffold and two-layer (called an independent tied) scaffold.

Putlog scaffolds have alternate standards tied to the façade and hence a two dimensional model is appropriate. This model can also be used to represent the behaviour normal to the façade of an independent tied scaffold. Diagonal bracing is used on the face farthest from the façade and this restrains this face of the scaffold to buckle normal to the façade. The rear face of the scaffold is restrained by ties and buckles with alternate standards buckling in opposite directions and hence a single column model can be used. These are shown in Fig. 7.

The spring stiffnesses for the different scaffold arrangements were shown to be

Putlog scaffold, standards buckling alternately $$k = \frac{48EI}{\left(2L_B\right)^3} \tag{2}$$

Putlog scaffold, standards buckling together $$k = \frac{192EI}{\left(2L_B\right)^3} \tag{3}$$

Independent tied scaffold $$k_\varphi = \frac{k_c}{1 + \dfrac{k_c L_B}{12EI}} \tag{4}$$

where k_c is the rotational stiffness of the ledger – standard connection, L_B the horizontal standard spacing and EI the flexural rigidity of the standard.

Prabhakaran et al [39, 74-76] developed a computer program including looseness and tested several theoretical models and showed that looseness was insignificant for diagonally braced frames but that for unbraced frames differences in response were obtained between applying out-of-plumb as a direct imperfection or applying a proportional side load. A result of the analyses including looseness in connections was that the ultimate load for the modelled frame was reduced by approximately 8% from the same frame without looseness. In addition Prabhakaran found that the bi-linear model determined using the Pallet-rack code BS EN 15512 [77], the tri-dimensional model given from the scaffold code BS EN 12810 [36] and a non-linear regression curve plotted to follow an experimental result all gave similar results implying that the simpler bi-linear model would be appropriate for analyses.

Experimental and theoretical studies conducted by Liu et al in Taiwan [78] on high scaffolds without diagonal bracing showed that the most important factors for structural safety were the length of exposed U-head at the top of the scaffold and the rotational capacity of joints. They used the approach of Beale and Godley [72] and derived approximate formulae for the design of these scaffolds. Recent research in China has been undertaken on theoretical and experimental models of tube-and-fitting scaffolds. Hu et al [79-81] undertook experiments on scaffold assemblies and showed that when the imperfections in the scaffold were correctly modeled that correspondence was made with analytical models. Li et al [82] developed a semi-empirical design tool for the analysis of scaffolds and compared the results with a finite element program with good correlation. A parametric study scaffold arrangements including span, height, width was undertaken for both stability and ultimate load configurations. Gao et al [83] measured the imperfections occurring in scaffold tubes and developed parametric stochastic models of the scaffolds. The authors applied the models to scaffold structures where they demonstrated that member imperfections significantly reduced the capacity of the scaffolds and recommended stricter quality control measures on allowable imperfections to ensure safe scaffolds. This result reinforces the conclusions on control discussed by Zhang et al [84]. Xie and Wang [85, 86] investigated high falsework and performed reliability analyses. They showed that incorrect alignment of vertical members significantly reduced the formwork capacity.

Tests on scaffold tower shoring systems were reported by Kao [87]. Yen et al [88-91] conducted tests on shoring systems up to 5 stories in height and proposed an empirical equation which could model the experimental results. However, as the experimental frame was only 5 stories tall the formula could not be used for higher systems without further work.

3.2 Proprietary scaffolds

Proprietary scaffolds can be divided into two classes – those made up of individual components such as Cuplok and those made up of modular construction such as ‘door’-type scaffolds.

3.2.1 *Proprietary scaffolds with individual components*

Holmes and Hindson [92] constructed tests on components of a proprietary scaffold used to construct a ‘birdcage’ falsework as used in bridge construction. They then tested a full-scale scaffold loaded by applying concrete blocks at the top of the scaffold. The collapse load was compared against the buckling load of the standards obtained using a Perry-Robertson formula. The results were varied with predictions of the theoretical load varying from 40% to 110% of the experimental load. The cases of large discrepancy were attributed to load eccentricity and coupler failure.

In the development of the Euronorms for scaffolding a series of tests on a prototype were conducted in Stuttgart. Fig. 8 shows the configuration of the prototype. The prototype structure was analysed by Godley and Beale [19, 93] and the results are shown in Fig. 9. It can be seen that 2-D and 3-D analyses ignoring spigot looseness give results where the maximum deflection was only half that observed in the tests. Only when contact elements at spigot joints were added to the analysis was good correlation between theory and experiment obtained. Maximum loads in all analyses were approximately the same. The authors showed that the behaviour of large proprietary scaffolds could be predicted using 2D models as there was little 3D interaction between failure modes which were predominantly either normal to the façade or parallel to the façade [19, 20]. Fig. 10 shows a 2D model of a large 3D scaffold which was based on the standard design given in BS 1139 [94]. As the analysis procedures available to the authors at that time did not allow full geometrical non-linear elasto-plastic analyses the authors undertook a non-linear geometric analysis and assumed failure occurred when the maximum loads columns determined in accordance with BS 5950 [95] were exceeded.

Note that in using 2D models diagonal bracing, treated as a bar element, which is eccentric can be included if its area is reduced using Eq. (5).

$$A_{red} = \frac{LkE}{k + 2AE} \tag{5}$$

where A_{red} is the reduced area, L the length of the brace, A the area of the bracing element, k is an axial stiffness determined from experiments and E Young's modulus. The stiffness of the spring (F/Δ) used to tie the façade in Fig 10(c) can be determined by

$$\frac{F}{\Delta} = \frac{1}{L^2}\left(\frac{L}{3EI} + \frac{1}{3k}\right)^{-1} \tag{6}$$

where L is the length of the tie and k the rotational stiffness of the ledger/standards or transom/standard connection. In the example in Fig. 10 three ledgers or transoms were connected to the same standard.

A 3D analysis of the scaffold modelled in [20] was also undertaken by Chan et al using stability functions [96] who obtained the same buckling load. The modes are shown to be primarily buckling normal to the faced in the lower elements only. Similar comparisons between 2D and 3D models were made by Lindner and Frölich [97] who compared their results with DIN 4421 [98] and by Gylltoft and Norelius [99], Gylltoft and Mroz [100] and Weinhold [101].

A detailed study of the Cuplok proprietary scaffold was undertaken at the University of Sydney Australia starting with an investigation of the spigot joint [102] using tests and non-linear computer models. The spigot joint was modelled by a similar procedure used in the the Euronorm for props [61] with results showing that if the spigot is concentrically loaded that the capacity of the standard was higher than an equivalent standard without a spigot but that eccentricity of loading significantly reduced the capacity. The Sydney research then tested the individual components followed by tests on falsework assemblies. Models were then constructed and probabilistic analyses undertaken to get reliability data [44-46, 103-108].

Jian et al [1099] undertook a series of full-scale tests on a proprietary scaffold and gave recommendations on the safe use of this scaffold system. Ohdo et al [110] tested several different forms of proprietary scaffold and undertook a risk analysis of the different types of wedge joint. They showed that the risk of failure of a given joint increases with increase in height of the scaffold.

Rodrigues used ABAQUS to develop structural models of the behaviour of Cuplok shoring towers showing the effects of eccentricities in member connections [111].

3.2.2. Modular scaffold systems

To speed erection and reduce the number of semi-rigid connections in a scaffold modular systems are popular in many countries. A typical module is shown in Fig. 11. All the component elements of a module are welded and spigots used to connect modules. The spigots are often treated as pins and eccentricity is ignored. Two modules parallel to each other are joined by diagonal braces with flattened ends assumed to be pinned.

Research into these structures was first reported by Chan and Peng and co-workers [112-119]. The first papers in 1995 and 1996 [112-114] described a finite element model using a polynomial beam element to analyse shoring scaffolds with between 1 and 3 stories. In all their models the buckling mode was approximately a sine wave normal to the modular sections. Papers [116, 118] included wooden shores on the top a modular scaffold and concluded that these shores significantly reduced the capacity of the structure but that reasonable agreement between tests and models could be obtained. As scaffolds frequently fail during the construction phase of a building the authors analysed placement loads on scaffolds and devised design guidelines [119-121]. The authors produced simplified methods of analysis and design [122, 123]. In 2003 they analysed pattern loading [124] and showed that the maximum load imposed on falsework often occurred at final loading and that the impact loading of fresh concrete was usually less than an equivalent uniform load throughout the scaffold. Chan et al [125] used geometric non-linear analyses on frames tested by Weesner and Jones [21] and obtained good correlation. A typical buckling mode of a modular scaffold is shown in Fig. 12. They then analysed the frame considered by Godley and Beale [19] (Fig. 10) and obtained higher loads than the simplified procedures adopted in [19]. Peng and Chan and co-workers then produced a series of papers comparing test results against non-linear analyses for a variety of structural configurations and loadings [126-137]. Chung and Yu [138] reported similar work. Yu et al [139, 140] investigated the stability of modular door scaffolds.

Huang et al [141, 142] developed simple numerical models for shoring systems made up of modular components and showed that 2D models gave accurate results when compared with tests. In addition Huang et al [143] developed a monitoring method to ensure that alerts could be given when false systems near collapse.

Weesner and Jones [21] described tests on three storey modular scaffolds from different manufacturers and compared the results against ANSYS models with moderate agreement. These tests have since often been used as example results for other researchers. Diógenes et al [144] showed that only 2 beam elements per member in ABAQUS were needed to analyse modular scaffolds.

A detailed finite element analysis of the nodes in a modular scaffold was undertaken by Pieńko and Błazik-Borowa [145] to determine the maximum capacity that can be applied to a node. Unfortunately no comparison was made with experiments to validate the analysis.

3.3. Timber and bamboo scaffolds

A conference was held in Hong Kong in 2002 [146] where the analysis and design of bamboo scaffolds was discussed. Papers on the design and assessment of bamboo columns have already been described [53, 60]. Tong [144] described the areas where bamboo scaffolding is currently used and design limitations of the scaffolds. Chung et al [56] outlined design calculations for bamboo scaffolds and gave examples of typical arrangements. So [148] showed that the performance of single layer bamboo putlog scaffolds could be improved by using metal tubes as the horizontal putlog connections. This was extended by So and Chan [149] where steel tubes were used as main standards with bamboo standards at intermediate positions.

Albermani et al [150] presented a double layer bamboo grid system where special PVC joints were used to improve structural performance. Finite element analyses of the joints were presented.

Peng [120, 121] and Peng et al [134] analysed and tested timber shoring systems and determined safe spacings for vertical and horizontal members.

3.4 Moveable scaffold structures

Moveable scaffold structures are used in large bridge projects. They are specialized structures and are only briefly covered here for completeness as a review has recently been produced by André et al [9]. André et al [151] also reviewed the existing design codes for bridge falsework and gave recommendations that the codes be revised to incorporate a risk management framework for bridge construction. A further paper [152] outlined the application of risk management techniques and defined a new robustness index so that failures could be reduced.

Di et al [153] constructed a finite element model to analyse the scaffolding framework and showed that a girder system could satisfy the Chinese design code. Recently Pacheco et al [154] discussed the changes to moveable systems with larger spans in the 70-90 m range. Design recommendations were made. Practical applications of such systems have been described by Póvoas [155] and Rosignoli [156].

4. Scaffold Loading

4.1 Dead and imposed vertical loads

The vertical load applied to scaffolds depends upon whether the scaffold is used as an access scaffold where it is applied throughout the scaffold or used as support structure for falsework such as a bridge deck during construction where the load is applied at the top.

When used for access scaffolds the European code BS EN12810 [36] and its predecessor BS 1139 [94] stipulated that 5 storeys must be considered as boarded although modern practice is often to board all storeys. The imposed load is then applied to the top storey with a reduced load to the storey below. These loading systems induce failure, normally by buckling in the bottom storeys. The buckled modes are either a sway buckling parallel to the façade or by buckling normal to the façade. See for example [20, 72].

Surveys undertaken by US National Bureau of Standards indicated that a significant proportion of failures were attributable to excessive loads applied to the falsework. El-Sheikh and Chen [157] undertook a survey of the loads on shore loads and showed that using the standard simplified design analyses that loads were underestimated by up to 27%. Rosowsky et al [158-160] measured the loads during placement and recommended that load factors in excess of 2 should be used to ensure safe design.

Hill [161] raised the issue as to whether the design loads for temporary structures should be lower than those for permanent structures as is often postulated by some designers as the structures are only in existence for a limited time. However, he argued that this can lead to failures.

Vertical loads applied to assemblies during construction have been considered by Peng et al [119, 124, 129] and reviewed in section 2.2.2. Pintado Llurba and Carlton [162] measured the loads occurring on two sites and compared them with the values determined from a 3D finite element simulation. They discovered that the simulation was unable to predict the experimental results varying from a load underestimation of 20% to and overestimation of 67%. They attributed the discrepancy to props being out-of-plumb and foundations not being as stiff as assumed in the analysis.

4.2 Seismic Loading

Limited research has been reported into the behaviour of scaffold structures under seismic conditions. Mohammadi and Zamani Heydari [163] argue that a reduced risk level for loads be adopted to account for the short life-span. This is in contrast to the research calculations by Hill [157] above.

Blair and Woods [164] described an analysis of a tube-and-fitting scaffold subjected to seismic loads when attached to the Fort Calhoun Nuclear Power Station in Omaha. They found that the friction between the base and the foundation was unable to resist the horizontal seismic forces and they recommended that scaffold structures be free to translate under seismic loads.

Lindley et al [165] undertook a series of shaking table tests on 6 foot and 12 foot scaffolds and concluded damping was high (coefficient 0.15), rubber mats would improve friction resistance, fundamental frequency is low (between 3-6 Hz), scaffolding is rugged and in their tests no structural failures except tie-off wire breaks occurred. They also found that single degree of freedom models could adequately model the structure.

Tests on scaffold connections were made by Satyan-Sharma and Brewer [166] who showed that standard connections made by the American Patent Scaffolding Company were able to take 1.5 times the load required in designing the Cook nuclear plant.

4.3 Wind Loading

Research in to wind loading applied to structures has been primarily concerned with loads on permanent structure with results codified into National and International standards such as CP3 [167], BS 6399-2 [168], BS EN 1991-1-4 [169]. In 1990

Lindner and Magnitzke [170] calculated that wind on scaffolds required tying the scaffold horizontally at 2 m intervals and vertically at 4 m intervals and that the load on the ties of a sheeted scaffold was up to five times the load on an unsheeted scaffold. Similar results were found by Beale and Godley [72]. The US Department of Labor [171] also emphasised the frequency and adequacy of ties. The wind speeds used in the US were described by Boggs and Peterka [172].

A conference was held by the UK Health and Safety Executive (HSE) at Buxton in 1994 [173]. Papers on the use of cladding in scaffolds, usually determined by wind tunnel tests or measuring forces on full-scale scaffolds were given [174-177]. Blackmore [178] commented that the BS 6399-2 [168] made allowance for temporary structures by reducing the probabilities of high wind speeds. He then gave a summary of scaffold failures where wind had played a part [179]. Williams [180] discussed the dynamic behaviour of fabric sheets suggesting that at that time modelling could only be achieved by wind-tunnel tests. Schnabel [181] described wind-tunnel tests on a cubical building 0.6 x 0.3 x 0.6 m conducted in Bavaria [182] in accordance with the German code DIN 4420 Part 1 [183]. Permeability of debris netting was shown to reduce the total force applied to the netting by over 20%. Hoxey [184] pointed out that the maximum force applied to a scaffold occurred when the wind was at an angle of approximately 30^o – 40^o from the plane of the façade. Wilson and Hollis conducted full-scale field tests on a large putlog scaffold 13.7 m high by 13.2 m wide at Buxton [185]. The scaffold was sheeted with different cladding materials and consisted of a single face, the rear being open. Measurements were made when the wind was within 7^o of the façade normal. Profiles of wind speed 10 m from the façade were recorded and the force at locations of the scaffold determined using the method described by Gylltoft [186]. Hollis published further results in [187].

A fundamental study of the wind loads on porous façade systems were determined experimentally by Gerhardt and Janser [188] where comparisons were made between full-scale and model experiments.

Between 2000 and 2007 Hino and Ohdo et al published a series of reports and papers on Japanese experiments into wind loads [189-197]. Wind tunnel experiments were undertaken with the scaffold placed around one or two sides of a rectangular building. Reliability analyses of the scaffold systems were also undertaken assuming that the scaffolds could be modelled as a series of series and parallel systems. Ohdo et al [196] also investigated a number of scaffold collapses and found that approximately

10% were due to wind. Recently, wind tunnel tests on scaffold systems surrounded by cladding with different numbers of storeys and different cladding arrangements have been reported by Wang et al [198, 199] and Irtaza et al [200, 201].

CFD analyses into wind loads on scaffolds were first reported by Yue et al [202] who analysed the behaviour of integral lift scaffolds - see Mi [203], Du [204], Yue et al [305] and Chen and Yuen [206] for a description of these scaffolds. Design calculations on the vibration effects sue to wind on integral lift scaffolds was reported by Li et al [207]. Yue and Yuan [202] used the CFD model proposed by Huang et al [208] where a combination of LES and RANS models were used to get pressure distributions around a model. These techniques were further used by Irtaza et al in analysing wind pressures acting on fully sheeted and porous clad scaffolds. [209-213]. The permeability of the porous netting was calculated by the procedures described by Kerry [214] and Browne et al [215]. They found that the wind loads on clad scaffolds on the lee face could be neglected in some cases and that the practice of not cladding the lowest level of a scaffold made negligible differences to the total wind pressure on the scaffold.

5. Design Procedures

There are only a few papers discussing design procedures for scaffold structures. For example, Mosallam and Chen [216] discuss the use of LRFD techniques to determine the adequacy of the structure during construction and Shapira [217] derived an algorithm to design towers.

Caspeele et al [218] commented that the Eurocodes do not provide a straightforward framework for probabilistic design of falsework and they suggested a procedure to derive partial factors appropriate to temporary structures.

Holický [219] suggested a reliability framework for the design of falsework structures.

Mehdizadeh et al [220] suggested the use of project management techniques to improve safety on sites.

Fang et al [221] outline a framework which compares the economic costs of bamboo scaffolding and compares them with metal scaffolding. A sensitivity analysis was conducted which showed that at the time of the paper metal scaffolding was more economic in Hong Kong than bamboo scaffolding.

O'Neill et al [222] present a knowledge based system to design proprietary scaffold structures such as Cuplok.

Sexmith and Reid [223] applied risk management techniques to derive safety factors for bridge falsework. They proved that standard timescales for wind loads may be unconservative.

In addition to the design codes referred to above [6, 28, 36-38, 61, 62, 68, 69, 98, 167, 168, 183] relevant design codes are – Australia [244-227], China [228-230], International Concrete Federation [231, 232], International Standards Institute (ISO) [233], Hong Kong [234] and USA [235-240]. Guidance for the safe design, erection and use of scaffolding can also be found in [70, 241-248].

6. Scaffold and falsework collapses

Many researchers have investigated the causes of scaffold collapses. In 1977 Matousek and Schneider surveyed 800 cases from European Insurance files [249] and in 1979 the ACI Committee surveyed 348 failures of concrete structures [242, 250]. In 1980 Walker [251] summarised the results of 120 failures predominantly in the UK with approximately 30% of the failures taking place during construction. No detailed investigation of the causes of failures was presented in these papers.

Lew [252] reported that the results of a review of serious construction collapses in the USA showed that common causes were errors in falsework design, lack of communication between designer and builder. The review suggested that design loads for construction and the calculations for falsework loads should be included in any construction plan.

In 1986 Hadipriono and Wang collected data on 85 falsework collapses [253, 254]. They reported that of the known causes of collapse that approximately 40% of the collapses occurred during pouring of concrete and 10% due to improper/premature falsework or falsework removal. Wind loads caused only one collapse. They emphasised that in most cases procedural errors due to inadequate design/construction and/or lack of inspection during concreting caused most failures. Hadipriono et al used fuzzy logic and event tree analysis to propose procedures to reduce failures [255-258].

During the six years from 1986-1993 the HK Health and Safety Executive (HSE) investigated 1091 safety related incidents sing the MARCODE HSE Database

[259]. Of these there were 471 collapses out of an estimated 7.5 million scaffold erections. The majority of the scaffold accidents were caused by faulty platforms including platform supports, human error, unsafe working procedures and faulty access arrangements. Inadequate guardrails also precipitated 44% of falls from scaffolds. The remaining failures occurred during erection/dismantling scaffolds and climbing up the outside of the scaffolds. A detailed analysis of the failure of scaffolds showed that 28% of the trigger events for scaffold collapse were caused by inadequate tying of the scaffold to the façade and 25% to structural overload. Collapses due to wind occurred on equal numbers of sheeted and unsheeted scaffolds. In 2003 Whitaker et al [260] reported on an analysis of over 3000 incidents in the UK by the Health and Safety Executive. They found that common structural causes were the use of defective components, unauthorised modifications to the structure of the scaffold as well as management failures in risk procedures and inadequate training,

Milojkovic and co-workers [261-263] conducted a survey of 56 scaffolds between 1996 and 1999 and showed that the same faults were still present. It was also reported by Maitra [259] that 13.5% of collapses took place in scaffolds less than 5m in height, 57% with scaffolds between 5 and 10 m in height, 22% in scaffolds between 10 and 15 m in height and 7.5% in scaffolds in excess of 15m in height. To investigate the effects of faults on scaffold safety Milojkovic [261, 262] constructed a model of a small domestic scaffold as shown in Fig. 13. This scaffold was analysed under various combinations of dead load, live load and wind load to determine the combination producing the lowest overall load factor. Faults were then introduced into the scaffold, typical of those found by Maitra [259]. It was found that inadequate foundations produced a 41% reduction in maximum capacity, excessive curvature of individual standards a 36% reduction, incorrect connections between standards and transoms 24% and inadequate tying 30% reductions. Combinations of faults were then introduced to correspond with poor site controls which showed that these could reduce the capacity to less than 10% of the original design capacity.

In 2001 the UK Health and Safety Executive published a report of an investigation of the faults inherent in scaffolding as erected [264]. The report summarised work previously carried out by Birch et al [265, 266] into props which showed that 16% were erected with an 'out-of-plumb' of 1.5^{o}. They commented that research by Burrows [267] showed that there was little control on sites into correct erection procedures. The authors conducted a series of measurements on 11 UK sites and reported that on most sites significant percentages of the scaffolds were erected with components outside the allowable tolerance limits of both the UK and European codes [36, 94]. Indeed on one site 50% of the legs were outside the UK code. The authors stated that they believed that the reason why collapses were relatively rare was due to the under-utilisation of scaffold capacity.

Halperin and McCann [268] surveyed 113 scaffolds in the US and found that 32% were either near to collapse or missing boards, guardrails or had inadequate access. They recommended improved site safety procedures.

André et al surveyed bridge falsework failures in 2012 [151] and showed that failures occurred due to inadequate falsework bracing (19%), inadequate main elements such as jacks, standards, couplers and ledgers (15%) and foundation failures (11%). They concluded that the probability of failure of temporary structures is higher than those in permanent structures and recommended factors of safety on vertical loads of at least 2.0.

Detailed forensic analyses of particular scaffold collapses are presented by El-Safety et al [269] (bridge falsework collapse), Pashang Pishen et al [270] (failure of supporting scaffold when pouring a concrete slab) and Andresen [271] (failure of an access scaffold adjacent to a hotel).

7. Conclusions

This paper has reviewed research into scaffold and falsework systems over forty years and shows the development of models for traditional tube-and-fitting, proprietary and bamboo scaffolds. The author recommends that looseness be considered when new codes are designed and that factors of safety for vertical loads be increased to 2.0 in the light of reliability research and analysis of scaffold collapses. The review also shows that limited research has been reported into seismic analysis of these structures and hence further research is required. Investigation into scaffold failures by both models and examination of failures shows that the majority of the failures occur due to poor site control.

Acknowledgements

The author wishes to acknowledge the support and cooperation of Dr M H R Godley (Slender Structures Ltd) for many years in the analysis of scaffold structures.

References

[1] Brand RE. Falsework and access scaffolds in tubular steel, McGraw-Hill; 1975.

[2] Wilshere CJ. Falsework, ICE Works Construction Guide. Thomas Telford, 1983.

[3] The Concrete Society. Formwork – a guide to good practice. 2nd Edition, Special Publication CS 030, Slough, 1995.

[4] Hurd MK. Formwork for concrete, 6th Edition, ACI Publication, SP4, CT98, 1995.

[5] Prefabricated Access Suppliers' and Manufacturers' Association. Operators code of practice for PASMA Aluminium Alloy Towers, 7th Edition, West Mersia, 2000.

[6] The American Concrete Institute, Guide to Formwork for concrete, ACI 347-04, USA, 2004.

[7] Beale RG. Review of Research into Scaffold Structures. In: Civil Engineering Computations: Tools and Techniques. Topping, BVH (Ed) 2007, Ch 12, p271-300.

[8] Chandrangsu T, Rasmussen KJR. Review of Past Research on Scaffold Systems. Research Report No. R905, Centre for Advanced Structural Engineering, Sydney University, Australia, 2009.

[9] André, J, Beale RG, Baptista AM. Recent advances and existing challenges in the design of bridge falsework systems. Civil Engineering and Environmental Systems 2013; 30(2):130-145.

[10] The Concrete Society and The Institution of Structural Engineers, Falsework a joint report, TRCS 4, London, 1971.

[11] Bragg SL. Final report of the Advisory Committee on Falsework. Her Majesties Stationary Office, London; 1975.

[12] British Standards Institution, BS 5975. Code of practice for falsework. London, 1996.

[13] Harung HS, Lightfoot E, Duggan DM. The strength of scaffold towers under vertical loading. The Structural Engineer 1975:53(1):23-30.

[14] Lightfoot E, Le Messurier A. Instability of Space Frames having Elastically-connected and Offset Members. In: Proceedings of the Second International Conference on Space Structures, Guildford, 1975, p143-149.

[15] Lightfoot, E. Oliveto, G. The Collapse Strength of Tubular Steel Scaffold Assemblies. Proceedings of the Institution of Civil Engineers 1977; 63(Part 2):311-329.

[16] Lightfoot E, Bhula D. The idealisation of scaffold couplers for performance tests and scaffold analysis. Materieux et Constructions 1977; 10(5-6):159-168.

[17] Lightfoot E, Bhula D. A test rig for scaffold couplers. Materieux et Constructions 1977; 10(5-6):168-173.

[18] Horne MR, Merchant W. The Stability of Frames, Pergamon, 1965.

[19] Godley MHR, Beale RG. Sway Stiffness of Scaffold Structures. Structural Engineer 1997; 75(1):4-12.

[20] Godley MHR, Beale RG. Analysis of large proprietary access scaffold structures. Proceedings of the Institute of Civil Engineers, Structures and Buildings 2001; 146(1):31-40.

[21] Weesner LB, Jones HL. Experimental and analytical capacity of frame scaffolding. Engineering Structures 2001; 23:592-599.

[22] Beale RG, Godley MHR. Numerical Modelling of Tube and Fitting Scaffold Systems. In: Proceedings of the Fourth International Conference on Advances in Steel Structures, Shanghai, 2005, p1375-1382.

[23] Ramanathan M. Hong Kong – Bastion of bamboo scaffolding. Proceedings of the Institution of Civil Engineers, Civil Engineering 2008; 161(CE4):177-183.

[24] Proverbs DG, Holt GD, Olomolaiye PO. Scaffolding for high-rise concrete construction: a French, German and UK comparison. In: Proceedings of the Institution of Civil Engineers, Structures and Buildings 1998; 128(2):59-66.

[25] Yip R, Poon CS. Comparison of timber and metal formwork systems. Proceedings of the Institution of Civil Engineers, Water and Resources Management 2008; 161(WR1):29-36.

[26] Allen A, Scholz H. Testing and evaluation of scaffolding tubes. Civil Engineer in South Africa 1987; 29(6):209-213.

[27] Hŭbner A, Saal H. Buckling behaviour of cold-formed scaffold tubes. In: Proceedings of the Eighteenth International Speciality Conference on Cold-

formed steel structures: Recent Research and Developments in Cold-formed Steel Design and Construction, Orlando, USA, 2006, p315-329.

[28] British Standards Institution, BS EN 1993-1-1:2005. Eurocode 3, Design of Steel Structures: Part 1.1: General Rules for Buildings. London, 2005.

[29] Brand RE. Stability of Tubular Scaffolding. Civil Engineering Public Works Review 1973; 68(808):991-1001.

[30] Lindner J, Hamaekers K. Load-carrying capacity of tubular spindles in scaffoldings. Stahlbau 1985; 54(8):225-231 (in German).

[31] Mansell DS, Agelidis N. Proof-Loading of Scaffolding. Proceedings of the American Society of Civil Engineers, Journal of the Engineering Mechanics Division 1981; 107(EM5):827-837.

[32] Milojkovic B, Beale RG, Godley MHR. Modelling scaffold connections. In: Computational Mechanics in the UK, 4^{th} ACME UK Annual Conference, Glasgow, 1996, p85-88.

[33] Volkel G, Zimmerman W. Supplementary Investigations for Couplers for Tubes of Scaffolding and Falsework. Stahlbau 1987; 56(11):335-342.

[34] Hertle R. Calculation of the Standard Designs of tube-and-fittings scaffolds in E-DIN 4420 Part 3. Stahlbau 1989; 58:303-308 (in German).

[35] Abdel-Jaber MS, Beale RG, Godley MHR, Abdel-Jaber M. Rotational strength and stiffness of tubular scaffold connectors. Proceedings of the Institution of Civil Engineers, Structures and Buildings 2009; 162(SB6):391-403.

[36] British Standards Institution, BS EN 12810-1:2003. Façade Scaffolds Made of Prefabricated Elements, Part 2: Methods of particular design and assessment. London, 2004.

[37] British Standards Institution, BS EN 12811-1:2003. Temporary works equipment, Part 1: Scaffolds-Performance requirements and general design. London, 2003.

[38] British Standards Institution, BS EN74-1:2005. Couplers, Loose Spigots and Base-Plates for use in Working Scaffolds and Falsework made of Steel Tubes; Requirement and test procedures. London, 2006.

[39] Prabhakaran U, Beale RG, Godley MHR. Analysis of scaffolds with connections containing looseness. Computers and Structures 2011; 89(21-22):1944-1955.

[40] Son KS, Park JJ. Structural analysis of steel pipe scaffolding based on the tightening strength of clamps. Journal of Asian Architecture and Building Engineering 2009; 9(2):479-485.

[41] Godley MHR. The performance of SGB Cuplok connectors. Oxford Polytechnic, Department of Civil Engineering, Building & Cartography, Report 221, 1990.

[42] Godley MHR. UK assessment of SGB Cuplok. Oxford Polytechnic, Department of Civil Engineering, Building & Cartography, Report 223, 1990.

[43] Volkel G. German Assessment for the Cuplok Scaffold System within the Framework of the Comparison of the Procedures in Different European Countries, Report N25-15404, Part 1, Test Report for CEN/TC53-WG2-N008, 1990 or Report Number T2381/1. Institute für Bautechnik, Berlin, 1990.

[44] Chandrangsu T. Advanced analysis and probabilistic-based design of support scaffold systems, PhD Thesis, Sydney University, Australia, 2010.

[45] Chandrangsu T, Rasmussen KJR. Full-scale tests and advanced structural analysis of formwork assemblies. In: Proceedings of the Sixth International Conference on Advances in Steel Structures, Hong Kong, 2009, p1083-1090.

[46] Chandrangsu T, Rasmussen KJR. Geometric Imperfection measurements and joint stiffness of support scaffold systems. In: Proceedings of the Sixth International Conference on Advances in Steel Structures, Hong Kong, 2009, p1075-1082.

[47] André, J, Beale RG, Baptista AM. Experimental Investigation of Bridge Falsework Cuplok Joints. In: VIII Congresso de Construção Metálica e Mista (8th Congress on Steel and Concrete Construction), Guimaráes, Portugal, 2011, pII795-804.

[48] Andre, J, Beale RG, Baptista AM. Experimental Investigation of Bridge Falsework Joints”. In: X Congresso de Construção Metálica e Mista e I Congresso Lus-Brasileiro de Construção Metálica Sustentável (10th Congress on Steel and Concrete Construction and 1st Brazilian Conference on Sustainable Steel Construction), Porto, Portugal, 2013, pII655-664.

[49] Van der Lugt P, van den Dobbelsteen AAJF, Janssen JJA. An environmental, economic and practical assessment of bamboo as a building material for supporting structures. Concrete and Building materials 2006; 20(9):648-656.

[50] Fu WY. Bamboo scaffolding in Hong Kong. The Structural Engineer 1993; 71(11):202-204.

[51] Chan SL, Xian XJ. Engineering and mechanical properties of structural bamboo. Technical Report, Research Centre of Advanced Technology in Structural Engineering. Hong Kong Polytechnic University, Hong Kong 2001.

[52] Chung KF, Yu WK. Mechanical properties of structural bamboo for scaffolding. Engineering Structures 2002; 24:429-442.

[53] Chung KF, Yu WK, Chan SL. Mechanical Properties and Engineering Data of Structural Bamboo. In: Proceedings of the International Seminar 'Bamboo Scaffolds in Building Construction' An alternative to metal scaffolds, Chung KF & Chan SL (Eds). Hong Kong, 2002, p1-24.

[54] Lu M, Yu WK, Chung KF. Reliability analysis for mechanical properties of structural bamboo. In: International Conference on Advances in Building Technology (ABT 2002). 2002, p637-644.

[55] Yu WK, Chung KF, Chan SL. Column buckling of structural bamboo. Engineering Structures 2003; 25(6):755-768.

[56] Yu WK, Chung KF, Chan SL. Axial buckling of bamboo columns in bamboo scaffolds. Engineering Structures 2005; 27(1):61-73.

[57] Chung KF, Chan SL, Yu WK. Design of Bamboo scaffolds. In: Proceedings of the International Seminar 'Bamboo Scaffolds in Building Construction' An alternative to metal scaffolds, Chung KF & Chan SL (Eds). Hong Kong, 2002, p65-88.

[58] Chung KF, Yu WK, Chan SL. Structural Stability of Bamboo Scaffolds. Research Centre of Advanced Technology in Structural Engineering. Hong Kong Polytechnic University, Hong Kong 2003.

[59] Chan SL, Chung KF. Stability design of scaffolds using circular hollow timber sections - bamboo. In: Proceedings of the International Seminar 'Bamboo Scaffolds in Building Construction' An alternative to metal scaffolds, Chung KF & Chan SL (Eds). Hong Kong, 2002, p55-64.

[60] Janssen JJA. Structural joints in Bamboo. In: Proceedings of the International Seminar 'Bamboo Scaffolds in Building Construction' An alternative to metal scaffolds, Chung KF & Chan SL (Eds). Hong Kong, 2002, p25-30.

[61] British Standards Institution, BS EN1065:1999. Adjustable telescopic steel props – Product specification, design and assessment by calculation and tests. London, 1998.

[62] DIN 4422. Telescopic steel props: Safety requirements, Testing, Beuth Veriag GmbH, Berlin, 1987.

[63] Feng, X. The Influence of semi-rigid connections on the behaviour of slender structures, PhD Thesis, Oxford Brookes University (formerly Oxford Polytechnic), UK, 1994.

[64] Salvadori A. Ultimate Strength of adjustable telescopic steel props according to standard EN1065. Journal of Constructional Steel research 2009; 65:1964-1970.

[65] André J, Baptista AM, Camotim D. Numerical investigation of adjustable telescopic steel props. In: Proceedings of the Twelfth International Conference on Civil, Structural and Environmental Computing, CC2009, Funchal Madeira, 2009.

[66] André, J, Baptista AM, Camotim D. Quality control and resistance of steel extendable telescopic props. In: VIII Congresso de Construção Metálica e Mista, Guimaráes, Portugal, 2011, pII611-620 (in Portuguese).

[67] Peng JL, Wang PL, Chan SL, Huang CH. Load capacities of Single-layer Shoring Systems – an experimental study. Advances in Structural Engineering 2012; 15(8):1389-1410.

[68] British Standards Institution, BS 5973:1993. Code of Practice for Access and Working Scaffold and Special Scaffold Structures. London, 1993.

[69] British Standards Institution, BS EN 12812. Falsework – Performance requirements and general design. London, 2004.

[70] NASC. TG20:08: Guide to Good Practice for Scaffolding with Tubes and Fittings, National Access and Scaffolding Confederation, London, 2008.

[71] Godley MHR, Beale RG. The Structural Behaviour of Tube and Fitting Access Scaffolding Systems, In: Proceedings of the Seventh International Conference on Computational Structures Technology, Lisbon, Paper 251, 2004, 16p.

[72] Beale RG, Godley MHR. Numerical Modelling of Tube and Fitting Access Scaffold Systems. Advanced Steel Construction 2006; 2(3):199-223.

[73] Beale RG, Godley MHR. Numerical Modelling of full-scale tube and fitting scaffold tests. In: Seventh EUROMECH Solid Mechanics Conference, Lisbon, Portugal, 2009, 12 p.

[74] Prabhakaran U, Nonlinear analysis of scaffolds with semirigid connections. PhD Thesis, Oxford Brookes University, UK, 2009.

[75] Prabhakaran U, Beale RG, Godley MHR. Second Order Analysis of Scaffolds with Semi-Rigid Connections. In: Proceedings of the Tenth International

Conference on Civil, Structural and Environmental Engineering Computing", Rome, Paper 158, 2005.

[76] Prabhakaran U, Godley MHR, Beale RG. Three-dimensional Second Order Analysis of Scaffolds with Semi-rigid Connections. Welding in the World 2006, 50(Aug-Sep):187-194.

[77] British Standards Institution, BS EN 15512:2009. Steel static storage systems – Adjustable pallet racking systems – Principles for structural design. London, 2009.

[78] Liu H, Zhao Q, Wang X, Zhou T, Wang D, Liu J, Chen Z. Experimental and analytical studies on the stability of structural steel tube and coupler scaffolds without X-bracing. Engineering Structures 2010; 32:1003-1015.

[79] Hu CM, Zeng FK. A study of experiment and numerical model on coupler steel tube falsework. Gongcheng Lixue/Engineering Mechanics 2010; 27(n SUPPL.2):280-283+293 (in Chinese).

[80] Hu CM, Ge Z, Wang J. Research on ultimate bearing capacity of coupler steel tube falsework with initial defect. Advanced Materials Research, Advances in Structures 2011; 163-167:32-35.

[81] Hu CM, Song FF, Fan XZ. Study of the Safety of the Fastener Steel Scaffolding. Advanced Materials Research 2011; 368-373:771-776 (in Chinese).

[82] Li HZ, Liu Z, Miao JY. The investigations of stability analysis of tube and coupler scaffold. Advanced Materials Research 2012, 594-597:730-733 (in Chinese).

[83] Gao H, Gao W, Li CX, Huo XX. Influence of the structural performance of steel tubular scaffold based on measured imperfection. Advanced Mechanics and Materials 2012; 256-259:754-757 (in Chinese).

[84] Zhang J, Shen F, Han F. Design and calculation of truss type formwork system. Journal of Shenyang Jianzhu University (Natural Science) 2005; 21(5):491-493+510.

[85] Xie N, Wang G. Test analysis on hidden defect in high falsework and its effect on structural reliability. In: Proceedings of the Eighth International Conference on Reliability, Maintainability and Safety (ICRAMS 2009), 2009, p1077-1080.

[86] Xie N, Wang G. Study on load-carrying capacity of super-high supports for formwork. Engineering Mechanics 2008; 25(AA01):148-153 (in Chinese).

[87] Kao CC. Analysis of safety behaviour for steel scaffold and vertical shore. Report, Department of Civil Engineering, National Taiwan University, Taiwan, 1981.

[88] Yen T, Chen, WF, Lin YC, Go GG, Ju MS, Huang YL et al. Research of steel scaffold accident during construction period (in Chinese), Labor Checking Report, The Council of Labor Affairs, Taipei, Taiwan, 156, 1993.

[89] Yen T, Chen WF, Lin YC, Huang YK, Chen HJ. Study of steel scaffold supports subjected to unsymmetrical loads and lateral loads (in Chinese), Labor Checking Report IOSH 83-S222, The Council of Labor Affairs, Taipei, Taiwan, 197, 1994.

[90] Yen T, Chen WF, Lin YC, Huang YK, Chen HJ. Study of the interaction between wooden steel scaffolds and development of collapse warning system" (in Chinese), Labor Checking Report IOSH 84-S121, The Council of Labor Affairs, Taipei, Taiwan, 95, 1995.

[91] Yen T, Chen WF, Huang YL, Chen WF, Chi RC, Lin YC. Design of scaffold shores for concrete building during construction. Journal of the Chinese Institute of Engineers 1997; 20(6):603-614.

[92] Holmes M, Hindson D. Structural behaviour of load bearing falsework. Proceedings Institution of Civil Engineers 1979; 67(2):721-41.

[93] Beale RG, Godley MHR. The Analysis of Scaffold Structures using LUSAS. In: Proceedings of LUSAS 95, Tewkesbury, UK, 1995, p10-24.

[94] British Standards Institution, BS 1139: part 5: 1990/HD1000: 1988. British Standard Metal Scaffolding: Part 5: Specification for materials, dimensions, design loads and safety requirements for service and working scaffolds made of pre-fabricated elements. London, 1990.

[95] British Standards Institution, BS 5950. Structural Use of Steel in Building: Part 1. London, 1987.

[96] Chan SL, Dymiotis C, Zhou ZH. Second-order analysis and design of steel scaffold using multiple eigen-imperfection modes. In: Proceedings of the Second International Conference on Advances in Steel Structures, Hong Kong, 2002, p312-327.

[97] Lindner J, Frölich, KC. Structural analysis for full-scale tests on scaffold assemblies. Stahlbau 1985; 5:142-146 (in German).

[98] DIN 4421. Falsework – Calculation, design and construction. Beuth Veriag GmbH, Berlin, 1982 (in German).

[99] Gylltoft K, Norelius Å. Prefabricated Scaffolds – Load Carrying Capacity. Swedish National Testing and Research Institute, Building Technology, Borås, SP- Metod 1172, 1992.

[100] Gylltoft K, Mroz K. Load-carrying capacity of scaffolds. Structural Engineering International 1995; 5(1):37-42.

[101] Weinhold J. On the validity of experimentally determined load carrying capacities of façade scaffolds. Bauingineer 1985:60:439-442 (in German).

[102] Enright J, Harris R, Hancock GJ. Structural Stability of Braced Scaffolding and Formwork with Spigot Joints, In: Proceedings of the Fifteenth International Speciality Conference on Cold-Formed Steel Structures, Orlando, 2000, p357-376.

[103] Chandrangsu T, Rasmussen KJR. Structural modelling of support scaffold systems. Journal of Constructional Steel Research, 2011; 67:866-875.

[104] Vaux S, Wong C, Hancock G. Sway stability of steel scaffolding and formwork systems. In: Proceedings of the Third International Conference on Advances in Steel Structures, Hong Kong, 2002, p311-319.

[105] Zhang H, Chandrangsu T, Rasmussen KJR. System Reliability of Steel Scaffold Systems. In: Proceedings of the Sixth International Conference on Advances in Steel Structures, Hong Kong, 2009, p1065-1073.

[106] Zhang H, Chandrangsu T, Rasmussen KJR. Probabilistic study of the strength of steel scaffold systems. Structural Safety 2010; 32(393-401.

[107] Zhang, H, Rasmussen KJR, Ellingwood BR. Reliability assessment of scaffold shoring structures for concrete formwork. Engineering Structures 2012; 36:81-89.

[108] Zhang, H, Rasmussen KJR. System-based design for steel scaffold structures using advanced analysis. Journal of Constructional Steel Research 2013; 89:1-8.

[109] Jian B, Yin K, Lu TY, Li ZH, Huang H, Fang Y. Experimental study on safety performance of plug-in steel-tube scaffold system. Journal of Sichuan University (Engineering Science Edition) 2008; 40(4):39-35.

[110] Ohdo, K, Takanashi S, Hino Y, Phongkumsing. Risk analysis of wedge joint temporary structures during construction. In: Applications of statistics and probability in civil engineering, Der Kiureghlan, Madanat & Pestana (Eds), Millpress, Rotterdam 2003, p1689-1694.

[111] Rodrigues A. Simulations of non-linear structural behaviour of shoring towers. Thesis diplôme d'Ingénieur, Université Blaise Pascal, France, 2010 (in French).

[112] Chan SL, Zhou ZH, Chen WF, Peng JL, Pan AD. Stability analysis of semi-rigid steel scaffolding. Engineering Structures 1995; 17(8):568-574.

[113] Peng JL, Yen T, Pan ADE, Chen WF, Chan SL. Structural Modelling and Analysis of Scaffold Systems. In: Proceedings of the First International Conference on Advances in Steel Structures 1996; 251-256.

[114] Chu AYT, Zhou ZH, Koon CM, Chan SL, Peng JL, Pan AD. Design of Steel Scaffolding using an Integrated Design and Analysis Approach, In: Proceedings of the First International Conference on Advances in Steel Structures, Hong Kong, 1996, p245-250.

[115] Peng JL, Pan ADE, Chen WF, Yen T, Chan SL. Structural modelling and analysis of modular falsework systems. ASCE Journal of Structural Engineering 1997; 123(9):1245-1251.

[116] Peng, JL, Pan AD, Rosowsky, DV, Chen WF, Yen T, Chan SL. High clearance scaffold systems during construction – I. Structural modelling and modes of failure. Engineering Structures 1996; 18(3):247-257.

[117] Peng JL. Experimental tests of joint stiffness of scaffolds and adjustment steel tube shores. Report of Structural Laboratory, No-20000601, Department of Construction Engineering, Chaoyang University of Technology 1999 (In Chinese).

[118] Peng, JL, Pan AD, Rosowsky, DV, Chen WF, Yen T, Chan SL. High clearance scaffold systems during construction – II. Structural analysis and development of design guidelines. Engineering Structures 1996; 18(3):258-267.

[119] Peng JL, Yen T, Lin I, Wu KL, Chen WF. Performance of scaffold frame shoring under pattern loads and load paths. ASCE Journal of Construction Engineering and Management 1997; 123(2):138-145.

[120] Peng JL. Stability analyses and design recommendations for practical shoring systems during construction. ASCE Journal of Construction Engineering & Management 2002; 128(6):536-544.

[121] Peng JL. Structural Modelling and design considerations for double-layer shoring systems. ASCE Journal of Construction Engineering & Management 2004; 130(3):368-377.

[122] Peng, JL, Pan AD, Chan SL. Simplified models for analysis and design of modular falsework, Journal of Constructional Steel Research 1998; 48(2-3):189-209.

[123] Peng, JL, Pan ADE, Chen WF. Approximate Analysis Method for Modular Tubular Falsework. ASCE Journal of Structural Engineering 2001; 127(3):256-263.

[124] Peng JL, Wu KL, Chen WF. Sequential pattern load modelling and warning-system plan in modular falsework. Structural Engineering and Mechanics 2003; 16(4):441-468.

[125] Chu AYT, Chan SL. Design of Steel Scaffolding by Nonlinear Integrated Design and Analysis (NIDA) and the Stability Function. In: Proceedings of the Second International Conference on Advances in Steel Structures, Hong Kong, 1999, p791-798.

[126] Chan SL, Peng JL. Performance-based design of steel scaffolding systems by stability analysis. In: Proceedings of the International Conference on Structural Stability and Dynamics, Taiwan, 2000, p205-210.

[127] Chu AYT, Chan SL, Chung KF. Stability of modular steel scaffolding systems – theory and verification. In: Proceedings of the International Conference Advanced Building Technology, Hong Kong, 2002, p621-8.

[128] Chan SL, Chu AYT, Albermani FG. Stability and simulation-based design of steel scaffolding without using the effective length method. International Journal of Structural Stability and Dynamics 2004; 3(4):443-460.

[129] Peng JL, Chan SL, Wu CL. Effects of geometrical shape and incremental loads on scaffold systems. Journal of Constructional Steel Research 2007; 63(4):448-459.

[130] Peng JL, Chen KH, Chan SL, Chen WT. Experimental and analytical investigations of scaffolds with anchor rod and plank. International Journal of Structural Stability and Dynamics 2009; 9(2):307-332.

[131] Peng JL, Chen KH, Chan SL, Chen WT. Experimental and analytical studies on steel scaffolds under eccentric loads. Journal of Construction Steel Research 2009; 65:422-435.

[132] Peng JL, Yen T, Kuo CC, Chan SL. Structural Analysis and Modelling of System Scaffolds used in Construction. In: Proceedings of the sixth International Conference on Advances in Steel Structures, Hong Kong, 2009, p1099-1108.

[133] Peng JL, Yen T, Kuo CC, Chan SL. Analytical and experimental bearing capacities of system scaffolds. Journal of Zhejiang University Science A 2009; 10(1):82-92.

[134] Peng JL, Wang PL, Huang YH, Tsai TC. Experimental studies of load capacities of double-layer shoring systems. Advanced Steel Construction 2010; 6(2):698-721.

[135] Kuo CC, Peng JL, Yen T, Chan SL. Experimental study of modular falsework system with wooden shores under various path loads. Advances in Structural Engineering 2008; 11(4):369-382.

[136] Liu YP, Chan SL. Second-order and advanced analysis of structures allowing for load and construction sequences. In: Proceedings of the Sixth International Conference on Advances in Steel Structures, Hong Kong, 2009, p1208-1217.

[137] Peng JL, Wu CW, Chan SL, Huang CH. Experimental and numerical studies of practical system scaffolds. Journal of Constructional Steel Research 2013; 91(12):64-75.

[138] Chung KF, Yu WK. Experimental and theoretical investigations on modular steel scaffolds. In: Proceedings of the Technical Seminar on Metal Scaffolding (Falsework) – Design, Construction and Safety, Hong Kong, Hong Kong Institute of Steel Construction, 2003, p13-23.

[139] Yu WK, Chan KF, Chan SL. Structural stability of modular steel scaffolding systems. In: Proceedings of the Second International Conference of Stability and Dynamics, Singapore, 2002, p418-423.

[140] Yu WK, Chung KF, Chan SL. Structural Instability of multi-storey door-type modular steel scaffolds. Engineering Structures 2004; 26:867-881.

[141] Huang, YL, Chen HJ, Rosowsky DV, Kao YG. Load carrying capacities and failure modes of scaffold-shoring systems, Part 1: Modelling and experiments. Structural Engineering and Mechanics 2000; 10 (1):53-66.

[142] Huang YL, Kao YG, Rosowsky DV. Load carrying capacities and failure modes of scaffold-shoring systems, Part 2: An analytical model and its closed- form solution. Structural Engineering and Mechanics 2000; 10(1): 67-79.

[143] Huang YL, Chen WF, Chen HJ, Yen T, Kao YT, Lin CW. A monitoring method for scaffold-frame shoring systems for elevated concrete formwork. Computers and Structures 2000; 78(5):681-690.

[144] Diógenes A, Holanda ÁS, Parente E Jr. Stability analysis of modular steel-shoring systems. Mecánica Computacional 2010; 29:659:672.

[145] Pieńko M, Błazik-Borowa E. Numerical analysis of load-bearing capacity of modular scaffolding nodes. Engineering Structures 2013; 48:1-9.

[146] Chung KF, Chan SL. (Eds). Proceedings of the International Seminar 'Bamboo Scaffolds in Building Construction' An alternative to metal scaffolds, Hong Kong, 2002.

[147] Tong AYC. Bamboo scaffolding – practical applications. In: Proceedings of the International Seminar 'Bamboo Scaffolds in Building Construction' An alternative to metal scaffolds, Chung KF & Chan SL (Eds). Hong Kong, 2002, p31-42.

[148] So FYS. Trade practice of bamboo scaffolds and mixed metal-bamboo scaffolds. In: Proceedings of the International Seminar 'Bamboo Scaffolds in Building Construction' An alternative to metal scaffolds, Chung KF & Chan SL (Eds). Hong Kong, 2002, p89-94.

[149] So F, Chan SL. Stability Design of mixed bamboo-steel scaffolding systems. In: Proceedings of the Sixth International Conference on Advances in Steel Structures, Hong Kong, 2009, p1109-1112.

[150] Albermani F, Goh GY Chan SL. Lightweight bamboo double layer grid system. Engineering Structures 2007; 29:1499-1506.

[151] André, J, Beale RG, Baptista AM. A survey of failures of bridge falsework systems since 1970, Proceedings of the Institution of Civil Engineers, Forensic Engineering 2012: 65(FE4):161-172.

[152] André, J, Beale RG, Baptista AM. Bridge Construction Equipment: An overview of the existing design guidance. Structural Engineering International 2012; 22(3):365-379.

[153] Di J, Chen AP, Dai P. Finite element analysis of movable scaffolding system in constructing continuous girder bridges. Journal of Chang'an University, Natural Science Edition 2005; 26(5):48-53.

[154] Pacheco P, Coelho H, Borges P, Guerra A. Technical challenges of large moveable scaffold systems. Structural Engineering International 2011; 21(4):450-455.

[155] Póvoas AA. The utilization of movable scaffolding systems in large spans. Structural Engineering International 3/2012; Technical Report 395-400.

[156] Rosignoli M. Robustness and Stability of Launching Gantries and Movable Shuttering Systems – Lessons Learned. Structural Engineering International 2007; 2:133-140.

[157] El-Sheikh M, Chen WF. Maximum probabilistic shore load in multi-storey R/C buildings. Computers and Structures 1989; 32(6):1347-1357.

[158] Rosowsky D, Huston D, Fuhr P, Chen WF. Measuring Formwork Loads during Construction. Concrete International 1994; 16(11):21-25.

[159] Rosowsky D, Huang YL, Chen WF, Yen T. Modelling concrete placement loads during construction. Structural Engineering Review 1994; 6(2):71-84.

[160] Peng JL, Rosowsky DV, Pan AD, Chen WF et al. Analysis of concrete placement load effects using influence surfaces. ACI Struct J 1996; 93 (2) :180–186.

[161] Hill H. Rational and irrational design loads for "temporary" structures. Practice Periodical on Structural Design and Construction 2004; 9(3):1984-2004.

[162] Pintado Llurba XC, Carton RJ. Modelling prop loads during concrete slab construction. Proceedings of the Institution of Civil Engineers, Structures and Buildings 2007; 160(SB4):221-229.

[163] Mohammadi J, Zamani Heydari A. Seismic and wind load considerations for temporary structures. Practice Periodical on Structural Design and Construction 2008; 13(3):128-134.

[164] Blair TG, Woods KD. Seismic scaffolding concerns? Let it 'walk'. Nuclear Plant Journal 1990; 8(3):76-77.

[165] Lindley D, Pandya D, Khanpour A. Estimating seismic response of free-standing scaffolding. Transactions of the Sixteenth International Conference on Structural Mechanics in Reactor Technology 2001, Paper 1027, 8 pages.

[166] Satyan-Sharma TR, Brewer SJ. Seismically qualified scaffolding improves safety and shortens outages. Nuclear Engineering International 1990; 35:121-123.

[167] British Standards Institution. CP3: Chapter V, Loadings. Part 2: 1972, Wind Loadings. London, 1972.

[168] British Standards Institution. BS6399-2: Loadings for Buildings. Code of Practice for wind load. London, 1997.

[169] British Standards Institution, BS EN 1991-1-4:2005+A1:2010. Eurocode 1. Actions on structures. General actions. Wind actions 2005.

[170] Lindner J, Magnitzke P. Stability of scaffold structures with sheeting. Stahlbau 1990; 59(2):39-44 (in German).

[171] U.S. Department of Labor. Wind Effects on Scaffolding. Wisconsin Safety Newsletter 2002; 1(1):1-4.

[172] Boggs DW, Peterka JA. Wind speed for design of temporary structures. In: Tenth ASCE Structures Congress, San Antonio, 1992, 4pp.

[173] HSE (Health and Safety Executive). Proceedings of the Conference on Wind Loading on Temporary Structures, Buxton, UK, 1994.

[174] Maitra A. Potential for reducing accidents by cladding scaffold. In: Proceedings of the Conference into Wind Loading on Temporary Structures, Buxton, HSE, 1994, p2-16.

[175] Maddocks G. Current UK practice in cladding scaffolds. In: Proceedings of the Conference into Wind Loading on Temporary Structures, Buxton, HSE, 1994, p33-45.

[176] Nieser H. Current German practices in cladding temporary structures. Proceedings of the Conference into Wind Loading on Temporary Structures, Buxton, HSE, 1994, p46-52.

[177] Cartwright P. The commercial advantages of cladding scaffolds. In: Proceedings of the Conference into Wind Loading on Temporary Structures, Buxton, HSE, 1994, p53-60.

[178] Blackmore PA. The use of BS 6399: Part 2: wind loads, for the design of temporary structures. In: Proceedings of the Conference into Wind Loading on Temporary Structures, Buxton, HSE, 1994, p61-73.

[179] Blackmore PA. The history of wind damage in the UK. In: Proceedings of the Conference into Wind Loading on Temporary Structures, Buxton, HSE, 1994, p17-32.

[180] Williams CJK. The structural design of fabric structures to resist wind loading. In: Proceedings of the Conference into Wind Loading on Temporary Structures, Buxton, HSE, 1994, p74-82.

[181] Schnabel P. Model experiments on covered scaffolding in a wind tunnel. In: Proceedings of the Conference into Wind Loading on Temporary Structures, Buxton, HSE, 1994, p99-116.

[182] Schnabel P. Final report on the research project Fluidic model experiments to determine wind loads on covered façade Report A/18/91, LGA Bavaria, Munich, 1993 (in German).

[183] DIN 4420, Part 1. Work and Guard Scaffolding; General regulations; Safety requirements; Tests, Beuth Verlag, Berlin, 1990 (in German).

[184] Hoxey R. Full-scale studies of wind-loading on light-weight structures, windbreaks and walls at Silsoe Research Institute. In: Proceedings of the Conference into Wind Loading on Temporary Structures, Buxton, HSE, 1994, p83-98.

[185] Wilson C, Hollis EJ. Research on the effects of wind loading on clad scaffold structures. In: Proceedings of the Conference into Wind Loading on Temporary Structures, Buxton, HSE, 1994, p117-136.
[186] Gylltoft K. Wind loads on sheeted scaffolds, A field study. Swedish National Testing Institute, Technical Report SP-RAPP 1986:27, 1986.
[187] Hollis EJ. Measurement of wind forces on net covered temporary scaffolds. In: Sixth International Conference on Structural Safety & Reliability, Innsbruck, Austria, 1993, p1639-1646.
[188] Gerhardt HJ, Janser HJ. Wind Loads on permeable façades. Journal of Wind Engineering and Industrial Aerodynamics 1994; 53:37-48.
[189] Ohdo K, Kareem A. Risk assessment of scaffolding system during construction under wind storms. In: Eighth International Conference on applications of statistics and probability, Sydney, Australia, 1999, p1183-1190.
[190] Ohdo K, Kareem A. Reliability analysis of Construction Scaffolding Systems under Wind Storms. In: Eighth ASCE Speciality Conference on Probabilistic Mechanics and Structural Reliability, 2000.
[191] Ohdo K, Hino Y, Phongkumsing S, Kareem S. Reliability Analysis of Temporary Scaffolding System in Strong Winds behind scaffolds. In: The Second International Symposium on Wind and Structures. Busan, Korea, 2002, p427-434.
[192] Hino Y, Phongkumsing S, Ohdo K, Takanashi S. Wind Pressure on scaffolds erected alongside of the building with holes in exterior walls. In: The Second International Symposium on Wind and Structures. Busan, S. Korea, 2002, p463-470.
[193] Phongkumsing S, Ohdo K, Hino Y. Risk Assessment for Prevention of Collapse by Scaffolds by strong wind based on wind tunnel experimental data. Anzen Kogaku Shinpojumu Koen Yokoshu 2003; 33:392-395.
[194] Hino Y, Ohdo K, Phongkumsing S, Maruta E, Kando K. Fundamental study on Wind Pressure acting on the Temporary Scaffolds. Specific research reports of the National Institute of Industrial Safety, Japan 2003; 2002:19-27 (in Japanese).
[195] Hino Y, Phongkumsing S. Study on the Estimation Method of Wind Pressure acting on the Temporary Scaffolds. Specific research reports of the National Institute of Industrial Safety, Japan 2005; 31:27-42 (in Japanese).

[196] Ohdo K, Takanashi S, Hino Y, Saito K. Measurement of wind load acting on scaffolds. Specific Research Reports of the National Institute of Industrial Safety, NIIS-SRR-NO.31. 2005 (In Japanese).

[197] Charuvisit S, Hino Y, Ohdo K, Maruta E. Makuta K. Wind tunnel experiment on wind pressures acting on the scaffolds in strong winds. Journal of Wind Engineering, JAWE 2007; 32(1):1- 10.

[198] Wang F, Tamura Y, Yoshida A. Wind loads on clad scaffolding with different geometries and building opening ratios. Journal of Wind Engineering & Industrial Aerodynamics 2013; 120:37-50.

[199] Wang F, Tamura Y, Yoshida A. Interference effects of a neighbouring building on wind loads on scaffolding. Journal of Wind Engineering & Industrial Aerodynamics 2014; 125:1:12.

[200] Irtaza H, Beale RG, Godley MHR. A wind tunnel investigation into the pressure distribution around sheet-clad scaffolds. Journal of Wind Engineering & Industrial Aerodynamics 2012; 103:86-95.

[201] Irtaza H, Beale RG, Godley MHR. Wind Tunnel Investigation of the Pressures acting on Sheet Clad Scaffolds. Report 397, School of the Built Environment, Oxford Brookes University 2010.

[202] Yue F, Yuan Y, Li GQ, Ye KM, Chen ZM, Wang ZP. Wind Load on Integral-lift Scaffolds for Tall Building Construction. ASCE, Journal of Structural Engineering 2005; 131(5):816-824.

[203] Mi JP. Trend of development of new-type scaffolds in China. Construction Technology 1999; 190(28):1-3 (in Chinese).

[204] Du RJ. Progress of technology and management of attached self-lifting scaffolds in China. Construction Technology 1999; 190(28):4-8 (in Chinese).

[205] Yue F, Yuan Y. Design methods of integral-lift tubular steel scaffolds for high-rise building construction. Structural Design of Tall and Special Buildings 2012; 21(1):46-56.

[206] Chen ZM, Yuan Y. Design analysis of an integral lifting scaffold for super-high buildings. In: Proceedings of the International Symposium of Civil Engineering in the 21st Century, Beijing, 2000, p227-232 (in Chinese).

[207] Li G, Feng Y, Yuan T, Ye K. Research on wind-induced vibration coefficient of self-climbing scaffold attached to tall buildings in construction. Journal of Earthquake Engineering and Engineering Vibration 2004; 24(5):62-67

[208] Huang S, Li QS, Xu S, Numerical evaluation of wind effects on a tall steel building by CFD. Journal of Constructional Steel Research 2007; 63(4):448-459.

[209] Irtaza H, Beale RG, Godley MHR. Determination of the Effects of Wind Load on Bare Tube Access Scaffold Structures Using Computational Fluid Dynamics. In: Proceedings of the Fifth International Conference on Advances in Steel Structures (ICASS 2007), Singapore, 2007, p637-642.

[210] Irtaza H. Experimental and computational determination of wind loads on netted/sheeted scaffolds, PhD Thesis, Oxford Brookes University, UK, 2009.

[211] Irtaza H, Beale RG, Godley MHR. Wind Loads on Netted Metal Access Scaffolds. In: Proceedings of the Sixth International Conference on Advances in Steel Structures (ICASS'09), Hong Kong, 2009, p1091-1098.

[212] Cortes-Quiroz CA, Irtaza H, Beale RG. A Numerical Study of the Effects of Wind acting in Different Directions on Clad Scaffolds Erected around a Low-rise Building. In: Proceedings of the Thirteenth International Conference On Civil, Structural and Environmental Engineering Computing, Chania, Crete, Paper 261, 2011.

[213] Irtaza H, Beale RG, Godley MHR, Jameel, A. Comparison of wind pressure measurements on Silsoe experimental building from full-scale observation, wind-tunnel experiments and various CFD techniques, International Journal of Engineering, Science and Technology 2013; 5(1):28-41.

[214] Kerry PR. Determination of Relative Permeability of Debris Netting Fabrics, HSE laboratory, Buxton, UK Report IR/L/FE/93/07, 1993.

[215] Browne M, McKinnon R, Bitsuamlak G, Kumar SK. Geometric scale effects in wind tunnel testing of porous screens. In: Twelfth International Conference in Wind Engineering, Cairns, Australia, 2007.

[216] Mosallam K, Chen WF. Design considerations for formwork in multi-storey concrete buildings. Engineering Structures 1990; 12(July):163-172.

[217] Shapira A. Rational design of shoring-tower-based formwork. Journal of Construction Engineering and Management, Proceedings of the American Society of Civil Engineers 1995; 121(3):255-260.

[218] Caspeele RCE, Robby CE, Steenbergen RDJM, Taewe LR. An adjusted partial factor method for temporary structures compatible with the Eurocode Framework. Civil Engineering & Environmental Systems 2013; 30(2):97-114.

[219] Holický M. Optimisation of the target reliability for temporary structures. Civil Engineering & Environmental Systems 2013; 30(2):87-96.

[220] Mehdizadeh R, Breysse D, Taillandier F, Niandou H. Dynamic and multi perspective risk management in construction with a special view to temporary structures. Civil Engineering & Environmental Systems 2013; 30(2):115-129.

[221] Fang D, Shen Q, Wu S, Liu G. A comprehensive framework for assessing and selecting appropriate scaffolding based on analytics hierarchy process. Journal of Safety Research 2003; 34:589-596.

[222] O'Neill S, Zhang H, Pawelak M. An industrial knowledge collaborative CAD system for scaffolding structures. In: proceedings of the thirteenth international conference on Civil, Structural and Environmental Engineering Computing, Chania, Crete, paper 111, 2011.

[223] Sexsmith RG, Reid SG. Safety factors for bridge falsework by risk management", Structural Safety. 2003; 25:227-243.

[224] Australian/New Zealand Standard, AZ/NZS 1576:2010, Scaffolding Part 1: General requirements, 2010.

[225] Parliament of Victoria, Scaffolding Regulations 1974, statutory rules promulgated under the Scaffolding Act 1971. Australia, 1974.

[226] Standards Australia. AS 3610. Formwork for concrete. Sydney, 1995.

[227] Standards Australia, AS/NZS 1576.1:1995. Scaffolding – Part 1 General Requirements, 1995.

[228] Shanghai Municipal Government: The Construction and Management Commission of the Shanghai Municipal Government. STCIS safety and technology code of integral-lift scaffold attached to structure in construction. DGJ08-905-99, 1999 (in Chinese).

[229] The Ministry of Construction of the People's Republic of China. JGJ 128, Safety and technical code for frame scaffolding with steel tubules in construction, 2000 (In Chinese).

[230] Chinese National Standard, CNS-4750, No. A2067, 1996 (In Chinese)

[231] Fib. Guidance for good bridge design, International Federation for Structural Concrete (fib), Switzerland, 2000.

[232] Fib. Formwork and Falsework for Heavy Construction. Guide to good practice. Bulletin 48, International Federation for Structural Concrete (fib), Switzerland, 2009.

[233] International Standards Organisation. ISO 2394: General principles on reliability for structures. Switzerland, 1998.

[234] Occupational Safety and Health Branch, Labour Department. Code of Practice for Metal Scaffolding Safety. Hong Kong, 2001.

[235] American National Standards Institute. Construction and Demolition Operations – Concrete and Masonry Work. ANSI A 10.9, 1983.

[236] Occupational Safety and Health Administration (OSHA. Safety and Health Regulations for Construction. Federal Register, V.53, 16, Washington, 1988.

[237] Office of Structure Construction. Falsework Manual, State of California, Department of Transportation, Revision No. 21, 1993.

[238] American Association of State Highway and Transportation Officials. Guide Design Specifications for Bridge Temporary Works, 1995.

[239] American Society of Civil Engineers. Design Loads on Structures During Construction, SEI/ASCE 37-02, 2002.

[240] American Association of State Highway and Transportation Officials. 2008 Interim Revisions to 'Guide Design Specifications for Bridge Temporary Works', 2008.

[241] Huizing JBS, Blakeley RWG, Ramsay G. Falsework. New Zealand Engineering 1977; 32(1):2-9.

[242] Allen DE. Errors in concrete structures. Structures Section, Division of Building Research, National Research Council of Canada, Ottawa, Canada, 1979.

[243] Touran A. Concrete formwork: Constructability and Difficulties. Civil Engineering Practice, Journal of the Boston Society of Civil Engineers Sect, ASCE 1988; 3(2):81-88.

[244] Christian J, Mir SU. Use of Integrated microcomputer package for formwork design. Journal of Construction Engineering and Management, Proceedings of the American Society of Civil Engineers 1987; 113(4):603-610.

[245] Hanna AS, Sanvido VE. Interactive horizontal formwork selection system Concrete International 1991; 13(8):50-56.

[246] Hanna AS, Willenbrock JH, Sanvido VE. Knowledge acquisition and development for formwork selection system. Journal of Construction Engineering and Management, Proceedings of the American Society of Civil Engineers 1991; 118(1):179-198.

[247] Tah JHM, Price ADM. Interactive computer-aided formwork design. Computers and Structures 1991; 41(6):1157-1167

[248] Chini A, Genaur G. Technical guidance available to designers of temporary structures. Structures Congress – Proceedings, ASCE, New York 1997; 2:979-984.

[249] Matousek M, Schneider. Studies on the safety problem in structures. Report No. 59, Institute of Structural Engineering, Swiss Federal Institute of Technology, Zurich, 1977 (in German).

[250] Franzec J. ACI Survey of Concrete Structure Errors. Concrete International 1979; 14-20.

[251] Walker AC. Study and Analysis of the First 120 Failure cases. In: Structural Failures in Buildings, The Institution of Structural Engineers, London, 1980, p15-40.

[252] Lew, HS. Construction failures and their lessons. Batiment International, Building Research & Practice 1984; 17(5):272-275.

[253] Hadipriono FC, Wang HK. Causes of falsework collapses during construction. Structural Safety 1987; 4(3):179-195.

[254] Hadipriono FC, Wang HK. Analysis of causes of falsework failures in concrete structures. Proceedings of the ASCE, Journal of the Construction Engineering and management 1986; 112(1):112-121.

[255] Hadipriono FC. Assessment of falsework performance using fuzzy set concepts. Structural Safety 1985; 3(Oct):45-57.

[256] Hadipriono FC. Approximate reasoning for falsework safety assessment. Structural Safety 1986; 4(2):131-140.

[257] Hadipriono FC, Lim CL, Wong KH. Event tree analysis to prevent failures in temporary structures. Proceedings of the ASCE, Journal of Construction Engineering 1986; 112(4):500-513.

[258] Hadapriono FC, Toh HS. Modified fault tree analysis for structural safety. Civil Engineering Systems 1989, 6(4):190-199.

[259] Maitra A. Accidents associated with scaffolding in the UK. Technical Seminar, Design and use of Temporary structures, Institution of Civil Engineers, London, 1997.

[260] Whitaker SM, Graves RJ, James M, McCann P. Safety with access scaffolds: Development of a prototype decision aid based on accident analysis. Journal of Safety Research 2003; 34(3):249-261.

[261] Milojkovic B. Factors of safety for standard scaffold structures, PhD Thesis, Oxford Brookes University, UK, 1999.

[262] Milojkovic B, Beale RG, Godley MHR. Determination of the Factors of Safety of Standard Scaffold Structures. In: Proceedings of the Second International Conference on Advances in Steel Structures, Hong Kong, 2002, p303-310.

[263] Beale RG, Godley MHR. Common causes of failure of metal scaffolds in the UK and stability checks on scaffolds. Proceedings of the Technical Seminar on Metal Scaffolding (Falsework) – Design, Construction and Safety, Hong Kong, Hong Kong Institute of Steel Construction, 2003, p62-79.

[264] Pallet PF, Burrow MPN, Clark LA, Ward RT. Investigation into aspects of falsework. HSE Books, Contract Research Report 394/2001, 2001.

[265] Birch N, Birch JG, Walker MBA. Effects of site factors on the load capabilities of adjustable steel props. Construction Industry Research and Information Association, CIRIA Report No. 27, London, 1971.

[266] Birch N, Walker MBA, Lee CT. Safe working loads for adjustable steel props, the influence of prop conditions and site workmanship. Construction Industry Research and Information Association, CIRIA Technical Note 79, London, 1977.

[267] Burrows B. The Organisation and Quality of Falsework Construction - A Socio-economic Study. PhD Thesis, University of Warwick, UK, 1989.

[268] Halparin KM, McCann M. An evaluation of scaffold safety at construction sites. Journal of Safety Research 2004; 35(2):141-150.

[269] El-Safty A, Zinszer M, Marcous G. Forensic investigation of a bridge construction scaffolding collapse. In: Proceedings of the 2008 Structures Congress Crossing the Borders, ASCE, 2008.

[270] Pashang Pishen Y, Shaffiei HR, Hatambeigi M. A case study of failure due to inappropriate usage of forming scaffold system. In: Proceedings of the 5th Congress on Forensic Engineering 2009: pathology of the Built Environment, ASCE 2009, p536-545.

[271] Andresen J. Investigation of a collapsed scaffold structure. Proceedings of the Institution of Civil Engineers, Forensic Engineering 2012; 165(FE2):95-104.

Figure captions

Fig.1. Types of coupler
(a) Right-angled coupler
(b) Putlog coupler
(c) Swivel coupler
Fig. 2. Typical moment-rotation curves
(a) Right-angled coupler
(b) Putlog coupler
Fig. 3. Schematic of tests to determine the moment-rotation curve about an axis parallel to a standard
(a) Ledger-standard
(b) Transom-standard
Fig. 4. Typical load-deflection curve for a proprietary scaffold connection
Fig. 5. Schematic of a putlog scaffold
Fig. 6. Schematic of an independent tied scaffold
Fig. 7. Double and single column models for tube-and-fitting access scaffolds
Fig. 8. Prototype scaffold
Fig. 9. Deflections normal to the prototype structure
Fig. 10. 2D models of a large proprietary scaffold
(a) Face furthest from façade
(b) Normal to the façade
(c) Face nearest the façade
Fig. 11. Schematic of a modular scaffold element
Fig. 12. Typical buckling mode of a 3 storey modular scaffold tower
Fig. 13. Model of a scaffold surrounding a domestic dwelling