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Review

# Scaffold research — A review

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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.

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## 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

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et al. have conducted recent reviews and have 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 then 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 of 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 50 mm 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

(a) Right-angled coupler (b) Putlog coupler (c) Swivel coupler

**Fig. 1.** Types of coupler

(a) Right-angled coupler
(b) Putlog coupler
(c) Swivel coupler.

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