Optimal arrangement for an efficient scaffold support system

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Abstract: Scaffold support system is primarily used as temporary support during construction. However, no clear guidelines exist for a direct means of predicting the load carrying capacity of scaffolding. To increase the efficiency of scaffolding system, the number of tubes to be moved should be addressed to reduce costs and improve speed of construction without jeopardising the load carrying capacity. This translates into fewer tubes to be lifted, transported, and shifted during assembly. The paper proposes a simple numerical space steel frame model to predict the load carrying capacity of scaffold support system and provide optimal arrangement for fast and safe construction. The numerical results reasonably predicted the load carrying capacity of initial scaffold system arrangements and provided corresponding optimal arrangements scaffold arrangements. The obtained optimal arrangements reduced the number of utilised tubes by at least 7.14% and up to 42.31% and resulted in 5.14% to 25% savings in direct cost.

Keywords: scaffold support system; space frames; steel tubes; buckling failure modes.


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1 Introduction

Scaffolding is mostly utilised as temporary structures in building construction process. In many cases, linear analysis procedure is performed to design scaffold systems to support construction loads. These loads can be gravity loads such as own weight of the members, fresh concrete, formwork, workers, and equipment or lateral loads like wind and earthquake. Scaffold systems are mainly consisting of modular units that are usually fabricated from slender members with flexible connections and are subjected to compressive forces. Stability problems are one of the main causes of collapse of these structures during construction. Thus, it is important to evaluate the buckling load of the modular shoring systems (support scaffolds) which depends not only on the geometry and material, but also on the boundary conditions, types of loading and connection between the members of the system (Zhang et al., 2010).

Beale (2014) reviewed and summarised research on scaffold and falsework structures in the past 40 years. He showed that prior to 1970 hand calculations commonly used effective lengths in the analysis of scaffolds. Results from standard calculations were summarised in text books such as those by Brand (1975) and Wilshere (1983) and design codes and manufacturer load tables (The Concrete Society, 1995; Hurd, 1995; Prefabricated Access Suppliers’ and Manufacturers’ Association, 2000; ACI 347-04, 2004). Previous shorter reviews have been conducted by Chandrangsu and Rasmussen (2009). André et al. (2013) reviewed design guidance on falsework for bridges. Zhang and Rasmussen (2013) examined the provisions for design by advanced analysis (second-order inelastic analysis) in the Australian Steel Standard (AS4100, 1998) and the AISC Specifications (AISC 360-10, 2010). The Australian Standard AS4100 uses a reduced section yield surface to incorporate resistance factors, while AISC 360 requires that the strength and stiffness of all members and connections are reduced by a factor of 0.9 to account for the uncertainties in member strength and stiffness. Another way to incorporate the resistance factor in advanced analysis is to use a system resistance factor for the frame strength. They presented a case study for the design of a typical semi-rigid steel scaffold structure using these design-by-advanced analysis methods where they assumed a system resistance factor of 0.9 for the purpose of comparing the Direct Advanced Analysis method with the AS4100 and AISC 360-10 methods. They concluded; however, that research efforts to develop system resistance factors for steel structures (including scaffold structures) should be performed using system reliability methods. Chandrangsu and Rasmussen (2011) described findings from various site measurements of out-of-straightness of the uprights, out-of-plumb of the frame, and loading eccentricity between the timber bearer and the U-head screw jack. The measurements were taken from different support scaffold construction sites before the pouring of concrete. They also reported the results of support scaffold joint tests. The tests were performed on randomly chosen used components to investigate the joint stiffness for rotations about vertical and horizontal axes. Tests were performed for various joint configurations, bending axes, and loading directions. They concluded that the statistical analysis of the data is useful for modelling and probabilistic assessment of support scaffold systems. Chan et al. (2005) and Zhang et al. (2010, 2012) analysed steel framed systems to capture the second-order effects of geometrical imperfections. They used three methods of modelling imperfections: the scaling of eigenbuckling modes (EBM), the application of notional horizontal forces (NHF), and the direct modelling of initial geometric imperfections (IGI). EBM was performed by carrying out an
eigenbuckling analysis on the structural model, and then scaling and superimposing the lowest eigenmode onto the perfect geometry to create an initial imperfect structural frame for the second-order structural analysis. In the NHF approach, additional lateral point loads were applied at the top of each column in one direction of the frame and initial member out-of-straightness could be represented by lateral distributed forces along each member. The IGI method consisted of applying an initial sway of the frame and an out-of-straightness to each column in the frame. They proposed that these same approaches could be applied to model the effects of initial imperfections in the analysis of scaffold systems. Prabhakaran et al. (2006) presented a computational algorithm for the second order analysis of three dimensional scaffold structures using stability functions. Their procedure incorporated the nonlinear behaviour of semi-rigid proprietary scaffold connections. The load-displacement results predicted by a computer program compared well with available experimental data on structures. However, the correlation of the nonlinear moment-rotation curve of connection joint could not be done due to lack of experimental data.

Experimental studies of critical loads on steel scaffolds have a common drawback (Peng et al., 2009a, 2009b; Yu, 2004; Yu et al., 2005; Kuo et al., 2008). Tests have to allow for the limitation of laboratory facilities with a hydraulic thrust head that only operates in a single direction. This leads to critical load studies of these scaffolds under the restrained boundary condition without any eccentricity load and with lateral restraint at the top. This type of concentric load with a lateral restraint condition is not quite the same as scaffolds under eccentric loads in actual construction conditions in job site. Peng et al. (2009a) investigated the effect of eccentric loads on steel scaffolding systems used in construction sites. The type of scaffold they considered was the door-shaped steel scaffold with an inner reinforced gable sub-frame. Their single-side cross-brace scaffolding systems with various eccentric loads are mainly focused on two issues, namely, the unrestrained boundary and the removal of cross-braces at the access location. This study shows that regardless of the lowest layer of cross-brace in a scaffold being removed or not, the critical load of a scaffolding system under an eccentric load is the lowest, whereas that of scaffolding system under a concentric load is the maximum. Peng et al. (2013) investigated the load capacities and failure modes of the scaffold structure in various stages in construction and it was based on experimental tests supplemented by analyses. The parameters investigated in their study included number of stories, ground heights, boundary conditions, presence of diagonal bracings and joint positions. The numerical studies quantified the load capacity of the scaffold against addition of diagonal bracings. They showed that their analyses and experimental tests confirmed the joint stiffness of different members used in the scaffold systems. They concluded that their findings would be useful for accurate determination of the ultimate load capacity of complex system scaffolds used in construction sites.

Nonlinear analysis is generally a complex task requires assigning resistance factors. This task has proved to be difficult for general steel structures due to the wide range of structural configurations, structural redundancy, ductility of components, and material properties. Therefore, This paper discusses a simple linear numerical analysis of scaffold systems used in the construction of concrete structures. The scaffold system is modelled as a space rigid jointed steel frame model and analysed using a commercial finite element software package, SAP2000, to obtain the load carrying capacity and to provide optimal design of its components. The aim is to reduce the weight and the number of the system
components for the same load carrying capacity using linear analysis and ignoring geometric and material nonlinearities.

2 Proposed scaffold system model

Most scaffold support systems consist of tubes, couplers, and timber boards (platform). The tubes are in general cylindrical and mostly made of steel. The couplers, right angle couplers and swivel couplers, or spigots are steel and they are used to connect tubes in a load bearing connection type. The boards are wood members used to provide a working surface and to carry uniformly distributed loads.

Figure 1 Scaffold system arrangements considered – dimensions kept constant for all arrangements (3 m × 6 m × 9 m), (a) first arrangement – vertical and horizontal tubes and no diagonal bracing tubes (b) second arrangement – more horizontal tubes with or without longitudinal diagonal bracing tubes (c) third arrangement – longitudinal diagonal bracing tubes with or without transversal diagonal bracing tubes (see online version for colours)
Optimal arrangement for an efficient scaffold support system

Figure 1  Scaffold system arrangements considered – dimensions kept constant for all arrangements (3 m × 6 m × 9 m), (a) first arrangement – vertical and horizontal tubes and no diagonal bracing tubes (b) second arrangement – more horizontal tubes with or without longitudinal diagonal bracing tubes (c) third arrangement – longitudinal diagonal bracing tubes with or without transversal diagonal bracing tubes (continued) (see online version for colours)

Figure 2  SAP2000 scaffold system arrangement models (space rigid steel frames) – dimensions kept constant for all arrangements (3 m × 6 m × 9 m), (a1) first arrangement SAP2000 model (a2) first arrangement but with more horizontal tubes model (b) second arrangement model (c) third arrangement model (see online version for colours)
The scaffolding system considered in this study carries gravity loads only. It is a 6 m long, 3 m wide, and 9 m high system simulating one bay by three story scaffolding, as shown in Figures 1 and 2. It comprises vertical, horizontal, and diagonal steel tubes. Diagonal tubes acting as bracing are used to stiffen the structure as necessary, in the longitudinal and/or transversal directions, and the vertical tubes transfer all the loads to the ground. Three scaffold system arrangements are analysed, in this study, for frame elastic buckling behaviour. First arrangement is a scaffold system with vertical and horizontal steel tubes and no bracing members as shown in Figure 1(a). The second scaffold system arrangement has vertical and horizontal steel tubes and diagonal bracing members in the longitudinal direction only, Figure 1(b). The third arrangement is a system with vertical and horizontal steel tubes and diagonal bracing members placed in both longitudinal and transversal directions, as in Figure 1(c). The bottom horizontal tubes are placed at 300 mm above ground. Top horizontal tubes are also at 300 mm but from top of the scaffold vertical tube members.
In this study, a simple steel rigid space frame model for the analysis of scaffold support systems, excluding geometric and material nonlinearities, is proposed and developed using SAP2000, as shown in Figure 2. All tubes of the scaffold system are steel tubes. All couplers are assumed rigid connections. The boards (platform) are assumed plate element. The base jacks at the bottom of the scaffold are modelled as fixed supports. The loads carried by the scaffold systems are only gravity loads, dead and live. No lateral loads are considered in this study.

### 3 Space frame elastic buckling analysis

The proposed simple model performs an elastic space frame buckling analysis to reasonably predict the load carrying capacity of the scaffold support system for the different buckling failure modes, and to provide optimal arrangement for a fast and safe construction under gravity loads. Due to gravity loads, the vertical tubes will be subjected to compressive loads. As the compressive loads increase, the vertical tubes tend to become unstable leading to buckling failure mode where the actual compressive stresses at the time of failure is less than the ultimate compressive stresses that the material can resist. The model is utilised to determine the magnitude of gravity loads that, when acting on the four vertical tubes simultaneously, will make the support scaffold system buckle. Consequently, the magnitudes of the buckling uniformly distributed loads acting on the scaffold working area (platform) can be calculated backward using tributary areas. Determining the magnitude of gravity loads that, when acting on the four vertical tubes independently with lateral loads applied, will cause the scaffold to buckle is intended for a future study.

Predicting the buckling loads of the different scaffold system arrangements considered in this study was carried out by utilising SAP2000 in which the scaffolds were modelled as 3D rigid jointed steel frames under gravity loads. Geometric, or P-Δ effects, and material nonlinearities are not considered in this study. Up to six buckling failure modes for each of the scaffold system arrangements are presented and their relevant buckling loads are reported. In this work, the design load or the load carrying capacity is assumed to be equal to the least buckling load that corresponds to first buckling failure mode.

### 4 Effects of different arrangements on scaffold bearing capacity

The effect of different arrangements shown in Figures 1 and 2 of a scaffold support system on its load bearing capacity was investigated. The vertical tubes transfer the loads to the ground. The horizontal tubes throughout the scaffold height act as confinement for the vertical members, whereas horizontal tubes near the base provide additional restraints. The diagonal tubes (bracings) are utilised to restrain the frame against excessive rotation associated with buckling collapse. The bracing provides a much greater stiffness against the frame rotation when installed in both directions, longitudinal and transversal.
For each scaffold arrangement model, up to six buckling failure modes are generated (Figures 3–4, 7–14, 16–17, 19–22) and their corresponding buckling loads are predicted using the proposed numerical model. The buckling modes shown in these figures and the values of the buckling loads listed in Table 1 indicate that the arrangement of the scaffold support system has a notable impact on its load bearing capacity. The load bearing capacity, or design load, considered in this study is the least buckling load which corresponds to the first buckling failure mode. Magnitudes of the predicted internal forces in scaffold members in two of the four evaluated scaffold arrangements were selected and are presented in Figures 15 and 18. The design results of the scaffold first arrangement show, as presented in Figure 5, that steel section HSS 3 × .120 is the lightest section for all the members to resist the first buckling failure load. To ensure that the steel tubes have the same unit weight throughout this study, the tube steel section HSS 3 × .120 is kept the same in scaffold second and third arrangements as well as in the predicted optimal arrangements. Section properties of HSS 3 × .120 are shown in Figure 6.

Figure 3 Model of scaffold first arrangement [of Figure 2(a1)] (see online version for colours)

Figure 4 Buckling modes of failure of scaffold first arrangement [of Figure 2(a1)], (a) first buckling failure mode (b) second buckling failure mode (c) third buckling failure mode (d) fourth buckling failure mode (e) fifth buckling failure mode (f) sixth buckling failure mode (see online version for colours)
Figure 4  Buckling modes of failure of scaffold first arrangement [of Figure 2(a1)], (a) first buckling failure mode (b) second buckling failure mode (c) third buckling failure mode (d) fourth buckling failure mode (e) fifth buckling failure mode (f) sixth buckling failure mode (continued) (see online version for colours)
Figure 4 Buckling modes of failure of scaffold first arrangement [of Figure 2(a1)],
(a) first buckling failure mode (b) second buckling failure mode (c) third buckling
failure mode (d) fourth buckling failure mode (e) fifth buckling failure mode
(f) sixth buckling failure mode (continued) (see online version for colours)

Figure 5 Size of tube sections used in the scaffold system [of Figure 2(a1)] – design (see online
version for colours)
Figure 6  Section properties of hollow circular tube used in this study, (a) US CUSTOMARY units (http://www.cim.mcgill.ca/~paul/HollowStruct.pdf) (b) SI system units (see online version for colours)

![Figure 6](http://www.cim.mcgill.ca/~paul/HollowStruct.pdf)

Source:  http://www.ruukki.com/Steel/Hollow-sections/Rectangular-hollow-sections/~/media/D67EBDA0E3014CEFB55E2C6A7F486BC8.ashx

Figure 7  Model of scaffold optimal first arrangement [of Figure 2(a1)] (see online version for colours)

![Figure 7](http://www.ruukki.com/Steel/Hollow-sections/Rectangular-hollow-sections/~/media/D67EBDA0E3014CEFB55E2C6A7F486BC8.ashx)
Figure 8  Buckling failure modes of scaffold optimal first arrangement [of Figure 2(a1)],
(a) first buckling failure mode (b) second buckling failure mode (c) third buckling
failure mode (d) fourth buckling failure mode (e) fifth buckling failure mode
(f) sixth buckling failure mode (see online version for colours)
Figure 8  Buckling failure modes of scaffold optimal first arrangement (of Figure 2(a1)),
(a) first buckling failure mode (b) second buckling failure mode (c) third buckling failure mode (d) fourth buckling failure mode (e) fifth buckling failure mode (f) sixth buckling failure mode (continued) (see online version for colours)
Figure 9  Model of scaffold first arrangement [of Figure 2(a2)] but with more horizontal tubes (see online version for colours)

Figure 10  Buckling modes of failure of scaffold first arrangement [of Figure 2(a2)] but more horizontal tubes, (a) first buckling failure mode (b) second buckling failure mode (c) third buckling failure mode (d) fourth buckling failure mode (e) fifth buckling failure mode (f) sixth buckling failure mode (see online version for colours)
Figure 10  Buckling modes of failure of scaffold first arrangement [of Figure 2(a2)] but more horizontal tubes. (a) first buckling failure mode (b) second buckling failure mode (c) third buckling failure mode (d) fourth buckling failure mode (e) fifth buckling failure mode (f) sixth buckling failure mode (continued) (see online version for colours)
Figure 10  Buckling modes of failure of scaffold first arrangement [of Figure 2(a2)] but more horizontal tubes, (a) first buckling failure mode (b) second buckling failure mode (c) third buckling failure mode (d) fourth buckling failure mode (e) fifth buckling failure mode (f) sixth buckling failure mode (continued) (see online version for colours)

Figure 11  Model of scaffold optimal first arrangement [of Figure 2(a2)] but with more horizontal tubes (see online version for colours)

Figure 12  Buckling modes of failure of scaffold optimal first arrangement [of Figure 2(a2)] but with more horizontal tubes, (a) first buckling failure mode (b) second buckling failure mode (c) third buckling failure mode (d) fourth buckling failure mode (e) fifth buckling failure mode (f) sixth buckling failure mode (see online version for colours)
Figure 12  Buckling modes of failure of scaffold optimal first arrangement [of Figure 2(a2)] but with more horizontal tubes, (a) first buckling failure mode (b) second buckling failure mode (c) third buckling failure mode (d) fourth buckling failure mode (e) fifth buckling failure mode (f) sixth buckling failure mode (continued) (see online version for colours)
Figure 12  Buckling modes of failure of scaffold optimal first arrangement [of Figure 2(a2)] but with more horizontal tubes, (a) first buckling failure mode (b) second buckling failure mode (c) third buckling failure mode (d) fourth buckling failure mode (e) fifth buckling failure mode (f) sixth buckling failure mode (continued) (see online version for colours)

Figure 13  Model of scaffold second arrangement [of Figure 2(b)] (see online version for colours)
Figure 14  Buckling modes of failure of scaffold second arrangement [of Figure 2(b)],
(a) first buckling failure mode (b) second buckling failure mode (c) third buckling failure mode (d) fourth buckling failure mode (e) fifth buckling failure mode (f) sixth buckling failure mode (see online version for colours)
Figure 14 Buckling modes of failure of scaffold second arrangement (of Figure 2(b)), (a) first buckling failure mode (b) second buckling failure mode (c) third buckling failure mode (d) fourth buckling failure mode (e) fifth buckling failure mode (f) sixth buckling failure mode (continued) (see online version for colours)
Figure 15  Scaffold member forces when system reaches its load carrying capacity (system of Figure 2(b)), (a) member axial forces (b) member torsional forces (c) member longitudinal shear forces (d) member transversal shear forces (e) member longitudinal bending moments (f) member transversal bending moments (see online version for colours)
Figure 16  Model of scaffold optimal second arrangement [of Figure 2(b)] (see online version for colours)

Figure 17  Buckling modes of failure of scaffold optimal second arrangement [of Figure 2(b)],
(a) first buckling failure mode (b) second buckling failure mode (c) third buckling failure mode (d) fourth buckling failure mode (e) fifth buckling failure mode (f) sixth buckling failure mode (see online version for colours)
Figure 17 Buckling modes of failure of scaffold optimal second arrangement [of Figure 2(b)], (a) first buckling failure mode (b) second buckling failure mode (c) third buckling failure mode (d) fourth buckling failure mode (e) fifth buckling failure mode (f) sixth buckling failure mode (continued) (see online version for colours)
Figure 17  Buckling modes of failure of scaffold optimal second arrangement [of Figure 2(b)], (a) first buckling failure mode (b) second buckling failure mode (c) third buckling failure mode (d) fourth buckling failure mode (e) fifth buckling failure mode (f) sixth buckling failure mode (continued) (see online version for colours)

Figure 18  Scaffold member forces when system reaches its load carrying capacity [optimal system of Figure 2(b)], (a) member axial forces (b) member torsional forces (c) member longitudinal shear forces (d) member transversal shear forces (e) member longitudinal bending moments (f) member transversal bending moments (see online version for colours)
Figure 18  Scaffold member forces when system reaches its load carrying capacity [optimal system of Figure 2(b)], (a) member axial forces (b) member torsional forces (c) member longitudinal shear forces (d) member transversal shear forces (e) member longitudinal bending moments (f) member transversal bending moments (continued) (see online version for colours)

Figure 19  Model of scaffold third arrangement [of Figure 2(c)] (see online version for colours)

Figure 20  Buckling modes of failure of scaffold third arrangement [of Figure 2(c)], (a) first buckling failure mode (b) second buckling failure mode (c) third buckling failure mode (d) fourth buckling failure mode (e) fifth buckling failure mode (f) sixth buckling failure mode (see online version for colours)
Figure 20 Buckling modes of failure of scaffold third arrangement [of Figure 2(c)].
(a) first buckling failure mode (b) second buckling failure mode (c) third buckling failure mode
(d) fourth buckling failure mode (e) fifth buckling failure mode
(f) sixth buckling failure mode (continued) (see online version for colours)
Figure 20  Buckling modes of failure of scaffold third arrangement [of Figure 2(c)],
(a) first buckling failure mode (b) second buckling failure mode (c) third buckling failure mode (d) fourth buckling failure mode (e) fifth buckling failure mode (f) sixth buckling failure mode (continued) (see online version for colours)

Figure 21  Model of scaffold optimal third arrangement [of Figure 2(c)] (see online version for colours)
Figure 22 Buckling modes of failure of scaffold optimal third arrangement [of Figure 2(c)], (a) first buckling failure mode (b) second buckling failure mode (c) third buckling failure mode (d) fourth buckling failure mode (e) fifth buckling failure mode (f) sixth buckling failure mode (see online version for colours)
Figure 22  Buckling modes of failure of scaffold optimal third arrangement [of Figure 2(c)], (a) first buckling failure mode (b) second buckling failure mode (c) third buckling failure mode (d) fourth buckling failure mode (e) fifth buckling failure mode (f) sixth buckling failure mode (continued) (see online version for colours)
5 Optimal arrangement of scaffold support system

To increase the efficiency of scaffolding system, the number and weight of tubes to be moved should be addressed to reduce labour cost and improve speed of construction without jeopardising the load carrying capacity. The aim is to reduce the weight and number of the scaffold tubes for the same load carrying capacity. This translates into less weight and less tubes to be lifted, transported, and shifted during assembly. To fulfil this aim, it is assumed that the capacity of the scaffold system is governed by the first buckling failure mode of the scaffold. The proposed numerical model is, however, able to predict six buckling failure modes for each of the four scaffold arrangements shown in Figure 2. The first buckling failure mode of any these scaffold system arrangements is taken as the governing mode, at which the scaffold system is deemed to have failed. Hence, the corresponding buckling load is considered the scaffold load bearing capacity and; accordingly, the scaffold was designed for the lightest tube sections.

Using the same tube steel sections HSS 3 × .120, the optimal scaffold system arrangement is arrived at when the buckling load of the first failure mode of the optimal system is equal to that of the initial system arrangement. This was achieved by trial and error, whereby the number of tubes was reduced and the scaffold was re-arranged, modelled, and analysed using the proposed model. Figures 3–4 and 7–12 show the scaffold first and relevant optimal arrangements as well as their buckling modes of failure. Figures 13–14 and 16–17 show the scaffold second and relevant optimal arrangements and their corresponding buckling modes of failure. Figures 19–22 show the scaffold third and relevant optimal arrangements and their resulting buckling modes of failure.

The buckling failure loads predicted by the proposed numerical model of the initial different scaffold system arrangements are listed in Table 1. Utilising trial and error technique, the initial scaffold was re-arranged and the new arrangement whose buckling failure load in the first mode is equal to that of the initial arrangement is considered the optimal scaffold arrangement. The proposed model numerical results of the optimal scaffold arrangements are listed in Table 1.

Table 2 shows the number of tubes utilised in each of the initial scaffold arrangements and the number of tubes needed to come up with corresponding optimal arrangements for the same load carrying capacity. Table 2 indicates that predicted optimal scaffold arrangements can reduce the number of utilised tubes by at least 7% and up to 42%. The predicted optimal arrangement can; therefore, increase the efficiency of scaffolding system as the number of steel tubes to be moved is reduced. As the number of tubes is reduced, the total weight of tubes is; hence, decreased. As a result of reducing the number of tubes, a reduction in labour and material costs and an increase in speed of construction without jeopardising the load carrying capacity can be achieved.
Table 1  Buckling loads in six failure modes of scaffold system and the corresponding buckling loads of the corresponding scaffold optimal arrangement (see online version for colours)

<table>
<thead>
<tr>
<th>Scaffold arrangement</th>
<th>Buckling failure loads (kN)</th>
<th>Governing buckling load (kN)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>First mode</td>
<td>Second mode</td>
</tr>
<tr>
<td>First scaffold arrangement [of Figure 2(a1)]</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>30.8</td>
<td>46.7</td>
</tr>
<tr>
<td>Optimal first scaffold arrangement [of Figure 2(a1)]</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>30.5</td>
<td>35.2</td>
</tr>
<tr>
<td>First scaffold arrangement but with more horizontal tubes [of Figure 2(a2)]</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Optimal first scaffold arrangement but with more horizontal tubes [of Figure 2(a2)]</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>59.9</td>
<td>85.1</td>
</tr>
<tr>
<td>Second scaffold arrangement [of Figure 2(b)]</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Optimal second scaffold arrangement [of Figure 2(b)]</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>101.9</td>
<td>112.9</td>
</tr>
<tr>
<td>Third scaffold arrangement [of Figure 2(c)]</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Optimal third scaffold arrangement [of Figure 2(c)]</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>534.9</td>
<td>649.5</td>
</tr>
</tbody>
</table>
Table 2 Reducing number of tubes utilised in optimal scaffold arrangement without changing the load carrying capacity (see online version for colours)

<table>
<thead>
<tr>
<th>Scaffold arrangement</th>
<th>Number of tubes utilised</th>
<th>Reduction in number of tubes utilised in optimal arrangement</th>
<th>Reduction % in number of tubes utilised in optimal arrangement</th>
</tr>
</thead>
<tbody>
<tr>
<td>First scaffold arrangement [of Figure 2(a1)]</td>
<td>28</td>
<td>2</td>
<td>7.14%</td>
</tr>
<tr>
<td>Optimal first scaffold arrangement [of Figure 2(a1)]</td>
<td>26</td>
<td></td>
<td></td>
</tr>
<tr>
<td>First scaffold arrangement but with more horizontal tubes [of Figure 2(a2)]</td>
<td>52</td>
<td>22</td>
<td>42.31%</td>
</tr>
<tr>
<td>Optimal first scaffold arrangement but with more horizontal tubes [of Figure 2(a2)]</td>
<td>30</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Second scaffold arrangement [of Figure 2(b)]</td>
<td>64</td>
<td>8</td>
<td>12.50%</td>
</tr>
<tr>
<td>Optimal second scaffold arrangement [of Figure 2(b)]</td>
<td>56</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Third scaffold arrangement [of Figure 2(c)]</td>
<td>76</td>
<td>6</td>
<td>7.89%</td>
</tr>
<tr>
<td>Optimal third scaffold arrangement [of Figure 2(c)]</td>
<td>70</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
6 Economics of the proposed optimal arrangements

Scaffold support system accounts for 30 to 70% of the construction cost for concrete-structure building frames (Peurifoy et al., 2011). As such, the selection and use of a scaffold support system is an important part of the economics of the project as a whole. Material and labour costs associated with any selected scaffold support system are essential components of the economic calculations to compare among different alternative systems. The following subsections briefly discuss the calculations associated with material and labour costs of the scaffold support system considered in this study.

6.1 Material cost

Assuming that the scaffolds are purchased (not rented), material costs are generally calculated as follows (Peurifoy et al., 2011):

\[
C = \frac{(P - S) \times USCRF(n, i) + S \times i}{Ny}
\]

where

- \( C \) material cost for one use
- \( P \) purchase cost
- \( N \) overall number of uses before disposal
- \( Ny \) annual number of uses
- \( n \) useful life (years), \( n = N/Ny \)
- \( S \) salvage value
- \( i \) annual interest rate
- \( USCRF \) is the uniform series capital recovery factor.

6.2 Labour cost

Labour cost is easy to calculate once labour productivity is determined. In many cases, however, labour productivity data for the operations of erecting and dismantling scaffolds are hard to obtain (Peurifoy et al., 2011). This is because labour productivity rates depend on work environment, worker skills, and project type and level of complexity. This is in addition to the effects of other productivity factors such as weather conditions, space congestion, regulatory rules, cultural habits, overtime, uncertainty, etc.

The following hypothetical example presents cost calculations and the saving that the proposed optimal arrangements can offer in direct material and labour costs. Other associated costs such as overheads and profits are ignored in this example. It is assumed that the market purchase cost per one ton of structural steel is about 7,000 Emirati Dirhams (AED). On average, in the United Arab Emirates construction industry, labour cost per ton of structural steel is about AED 3,000, excluding overheads and profit. This labour cost figure does not account for any overtime rates, which are normally higher.
6.3 Cost calculations example

A hypothetical example is presented in this paper considering the use of 100 pieces of the scaffold support arrangements for a small- to medium-size project. In this example, it is assumed that the scaffolds are used throughout their full useful life, and there is no salvage value ($S$) at the end of the useful life. Also, it is assumed that the scaffolds will be used for three years for a total of 120 uses with an average of 40 uses per year. It is assumed that the average interest rate is 5% per year. Comparisons of direct material and labour costs of the initial arrangements with their corresponding optimal ones are presented in Table 3. Sample calculations for the direct cost values shown in Table 3 and the associated savings in direct costs for case 1 are shown below:

1. For the initial arrangement of case 1 scaffolds:

   \[
   \text{The total material purchase cost} = 7,000 \times 0.584 \times 100 = \text{AED } 408,800
   \]

   \[
   \text{Material cost per use } (C) = 408,800(A / P, 5\%, 3) / 40 \\
   = (408,800 \times 0.3672) / 40 = \text{AED } 3,752.78
   \]

   \[
   \text{Total material cost for the initial arrangement of case } 1 \text{ scaffolds} = 3,752.78 \times 120 \\
   = \text{AED } 450,334
   \]

   \[
   \text{Total labour cost} = 3,000 \times 0.584 \times 100 = \text{AED } 175,200
   \]

   \[
   \text{Total labour and material cost} = 450,334 + 175,200 = \text{AED } 625,534
   \]

2. For the optimal arrangement of case 1 scaffolds:

   \[
   \text{The total material purchase cost} = 7,000 \times 0.554 \times 100 = \text{AED } 387,800
   \]

   \[
   \text{Material cost per use } (C) = 387,800(A / P, 5\%, 3) / 40 \\
   = 387,800 \times 0.3672) / 40 = \text{AED } 3,560
   \]

   \[
   \text{Total material cost for the initial arrangement of case } 1 \text{ scaffolds} = 3,560 \times 120 \\
   = \text{AED } 427,200
   \]

   \[
   \text{Total labour cost} = 3,000 \times 0.554 \times 100 = \text{AED } 166,200
   \]

   \[
   \text{Total labour and material cost} = 427,200 + 166,200 = \text{AED } 593,400
   \]

   \[
   \text{Saving in direct material and labour costs (case 1)} = 625,534 - 593,400 \\
   = \text{AED } 32,134
   \]

   \[
   \text{Percentage of savings in direct material and labour costs (case 1)} = (32,134 / 625,534) \times 100 = 5.14\%
   \]
Optimal arrangement for an efficient scaffold support system

Similarly, the amounts of savings in direct material and labour costs for cases 2, 3, and 4 in Table 3 are calculated as AED 234,575, AED 317,052, and AED 249,572, respectively. It can be noted that case 2 [Figure 1(a1)] provided the highest savings using the optimal arrangement. These savings are for direct costs and for the project’s scaffolds item only. The savings are expected to be higher if labour overtime rates, indirect costs, profit, higher interest rate are also considered in the calculations. Also, if the optimal arrangements are used for large-size projects, the savings are expected to be substantial.

Table 3: Total direct costs (in AED) and expected savings in direct cost for the four cases of the initial and optimal arrangements

<table>
<thead>
<tr>
<th>Case 1</th>
<th>Case 2</th>
<th>Case 3</th>
<th>Case 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial arrangement</td>
<td>Initial arrangement</td>
<td>Initial arrangement</td>
<td>Initial arrangement</td>
</tr>
<tr>
<td>Mass (tons):</td>
<td>0.584</td>
<td>0.876</td>
<td>1.276</td>
</tr>
<tr>
<td>Material purchase cost:</td>
<td>408,800</td>
<td>613,200</td>
<td>893,200</td>
</tr>
<tr>
<td>Material cost per use:</td>
<td>3,753</td>
<td>5,629</td>
<td>8,200</td>
</tr>
<tr>
<td>Material total cost:</td>
<td>450,334</td>
<td>675,501</td>
<td>983,949</td>
</tr>
<tr>
<td>Labour cost:</td>
<td>175,200</td>
<td>262,800</td>
<td>382,800</td>
</tr>
<tr>
<td>Total direct cost:</td>
<td>625,534</td>
<td>938,301</td>
<td>1,366,749</td>
</tr>
<tr>
<td>Optimal arrangement</td>
<td>Optimal arrangement</td>
<td>Optimal arrangement</td>
<td>Optimal arrangement</td>
</tr>
<tr>
<td>Mass (tons):</td>
<td>0.554</td>
<td>0.657</td>
<td>0.98</td>
</tr>
<tr>
<td>Material purchase cost:</td>
<td>387,800</td>
<td>459,900</td>
<td>686,000</td>
</tr>
<tr>
<td>Material cost per use:</td>
<td>3,560</td>
<td>4,222</td>
<td>6,297</td>
</tr>
<tr>
<td>Material total cost:</td>
<td>427,200</td>
<td>506,626</td>
<td>755,698</td>
</tr>
<tr>
<td>Labour cost:</td>
<td>166,200</td>
<td>197,100</td>
<td>294,000</td>
</tr>
<tr>
<td>Total direct cost:</td>
<td>593,400</td>
<td>703,726</td>
<td>1,049,698</td>
</tr>
</tbody>
</table>

Savings in direct cost (AED): 32,134 234,575 317,052 249,571
% of savings in direct cost: 5.14% 25.00% 23.20% 14.90%

7 Conclusions

To increase the efficiency of support scaffolding systems, optimal arrangements of scaffold support systems are proposed. The scaffold support system arrangements considered in this study are subjected to gravity loads and are numerically modelled and analysed using a proposed simple numerical space steel frame model. The proposed model performs an elastic space frame buckling analysis to reasonably predict the different buckling failure modes of the initial arrangements of the scaffold support systems considered in this study. The load carrying capacity of each initial arrangement of the scaffold support systems is assumed to be equal to the buckling failure load of the first mode of failure. Upon obtaining the load carrying capacity of each scaffold arrangement, the proposed model is utilised to predict, by trial and error, a corresponding optimal scaffold support system arrangement for a fast and safe construction. The numerically predicted optimal arrangements can
reduce the number of utilised tubes by at least 7.14% and up to 42.31% result in 5.14% to 25% savings in direct cost for almost the same load carrying capacity of that of the initial scaffold support system arrangement.

This translates into fewer weight and less tubes to be lifted, transported, and shifted during scaffold assembly, less labour and material costs, and improved speed of construction.

References

ACI 347-04 (2004) The American Concrete Institute Guide to Formwork for Concrete, USA.