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Stability analysis of different types of steel scaffolds

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ABSTRACT

Scaffolds are temporary structures commonly used in construction to support various types of loads. Recently their collapse is becoming more common as shown by the number of accidents and injuries reported. The paper analyzes the main flaws and imperfections that could lead to the collapse of the scaffoldings. The study has been focused at the numerical level on three different types of steel scaffoldings: (i) joint tubes, (ii) multidirectional and (iii) prefabricated systems, which are commonly used in Italy. Several finite element simulations under different loading conditions on three types of steel scaffoldings have been performed, taking into account the imperfections during the assembly at the construction site, the base boundary conditions and the effects of lateral restraint arrangement. Finally, the study proposes an empirical formula to identify the critical load of different types of steel scaffoldings based on the number of story levels and the type of boundary conditions.

1. Introduction

Steel scaffolds are extensively used to support permanent and temporary works during different stages of construction all over the world. The collapse of scaffoldings usually leads to work delays and it is also been responsible for numerous worker injuries (Fig. 1). In 2001, a study carried out by the Department of Hygiene and Safety Service at Work (SPISAL) of Treviso in Italy highlighted some common characteristics of the recorded accidents [1]. As shown in Fig. 1 most of the accidents happen in the construction sector, followed by injuries caused during the installation, maintenance and use of earth-moving machinery.

The consequences of overloading scaffoldings are evident in the recent accidents. In particular, in a coal power plant in Barangay Malaya (Pililia town, 2013), at an art workshop in Xianrendong (village, Changping district) in northern Beijing (2012), in a building site in Putney, in south-west London (2012), in the Guangxi Medical University Library accident (2007), in which seven construction workers were killed [2]. Usually the structural failure of the scaffoldings occurs due to the inadequate design, the poor installation, and the unknown overloads on site [3–5]. Therefore, a precise estimation of the load carrying capacity of scaffoldings on site, to guarantee the proper safety level of construction workers, is mandatory.

1.1. Literature review

The analysis of prefabricated steel frame scaffolding uniformly loaded has been considered in the work by Chan et al. [6], considering different types of connections (e.g. pin, semirigid and rigid joints) using the concept of effective stiffness, even if the load eccentricity is not taken into account. Later Peng et al. [4,7] analyzed the combination of modular steel scaffolds and wooden shores, used for temporary support during the construction of high-clearance concrete buildings. Additional experimental tests of steel frame scaffolding systems have been carried by Weesner et al. [8] and the output data has been used to calibrate the three-story scaffolding numerical model developed with a commercial software. The model assumes rigid joints between stories and pin joints at the top and the bottom of the model. The numerical results of the elastic buckling analysis were higher than the values of the experimental tests with difference between 6% and 17%. Similar studies were carried out by Yu et al. [5,9] and Chung et al. [10], but for a analyzing the behavior of multi-story prefabricated scaffolding. The novelty of the study is that the finite element analysis has been performed taking into account different types of connections between floors. Furthermore, Peng et al. [11] tested the door-shaped steel scaffoldings. For simulating the lateral unrestrained condition of the top part during the tests, the scaffolding was placed upside down. The bottom part of the upside down scaffolding is the top part of the original scaffolding and it rests on steel plates that ensure an unrestrained movable condition. A barycentric load and three eccentric loads were considered in the

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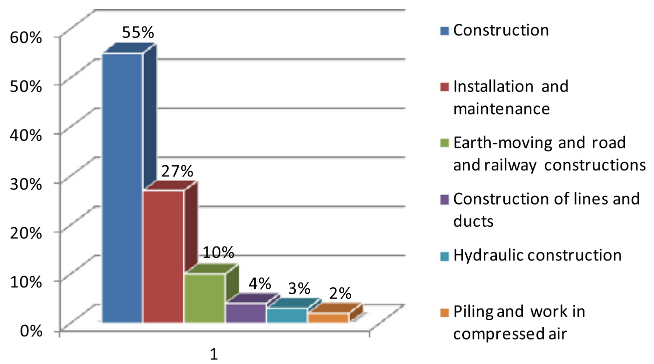

Fig. 1. Distribution of injuries based on the construction sector (). Adapted from [1]

tests, while some cross-braces were also removed to analyze how varies the value of the critical load. Recently Zhang et al. [12] has investigated in probabilistic terms the strength of scaffoldings. In particular, they focused on the effects of uncertainties in the geometrical and mechanical parameters as well as the ultimate strength of the multi-story steel scaffolding. Three-dimensional second-order inelastic FE models were used to compute the ultimate limit strength and compared with the experimental results. A similar study was performed by Liu et al. [13] where they analyzed the strength and failure modes of steel tubes and coupler scaffolds (STCS's). Twelve full-scale static tests were conducted on twelve specimens that were pinned at the base and have a roller on the top. Experimental results have shown that the typical collapse mode for scaffolding is the lateral buckling. FEM models as well as a simplified model were developed for the analysis and the design of STCS to recommend design guidelines for practice.

Chandrangsu and Rasmussen [14] analyzed the measurements of geometric imperfections of support scaffoldings collected from four different construction sites around the Sidney area. The analyzed measurements were the *out-of-straightness of the standards* (uprights), *out-of-plumb of the frame* and *loading eccentricity* between the timber bearer and the U-head screw jack. The results of the experimental tests on cuplok joints were presented discussing the semi-rigid joint behavior observed during the tests in probabilistic terms. In another work, Chandrangsu and Rasmussen [15] proposed different methods for modeling spigot joints, semi-rigid upright to the beam connections and base plate eccentricities. Zhang et al. [16] analyzed typical steel scaffold shoring structures utilizing recent survey data on geometric and mechanical properties of steel scaffold members, and a second order inelastic structural analysis model. The concluded in their analyses that the variability in system strength mainly arises from the uncertainties associated with load eccentricity, material and geometric properties of the standards. Prabhakaran et al. [17] have developed an algorithm to model the scaffold behavior which describes the full moment-rotation curve including looseness as well as the nonlinear loading and unloading behavior. The results have shown that for the sway frames, the looseness reduces the capacity significantly, but for the braced frames, the looseness has less effect.

Recently, Błazik-Borowa and Szer [18] attempt at determining the reasons of the hazardous incidents of workers on scaffolds. Reasons of common failures are traced, with the activities that contribute to decrease unsafe situations as well. Subsequently, Błazik-Borowa and Gontarz [19] investigate numerically the influence of geometric imperfections on the static stability of façade scaffolding. Increase of internal forces due to imperfections is recognized, with the highest increase occurrence when imperfections occur in the lowest elements. Table 1 summarizes the relevant aspects of the literature review.

The purpose of this research is to analyze the behavior of steel scaffolding focusing on safety concerns that may arise on site. Three different types of steel scaffoldings which are usually used in practice in Italy have been considered. The major flaws or imperfections sequences that lead more easily to the collapse of the scaffolding have been analyzed. Different types of improper installations have been also modeled removing the cross-bracings in sequence during the analyses. Finally, the paper proposes an empirical formula to determine the critical load of a scaffold using parameters such as the scaffolding typology, the number of floors and the different boundary conditions.

Both 1-bay 1-story and multi-story models have been analyzed for the three types of scaffoldings (joint tubes, multidirectional and prefabricated scaffolds).

2. Steel scaffolding - typologies of construction

Scaffoldings are provisional multistory reticular structures and until the early twentieth century, were mainly made of wood (e.g. the most famous wood scaffolding was the one made by Michelangelo for the construction of the dome of St. Peter's Basilica in the Vatican), while the modern ones are almost all made of steel and sometimes aluminum. In Asian countries are also used bamboo structures [10]. This section describes the most commonly used types of steel scaffoldings in Italy which can be grouped in three types:

- *Joint tubes system:* also known as pipes Innocenti scaffolding (after the inventor Ferdinando Innocenti), which are very versatile and suitable for any type of use, but they need more work to be assembled.
- *Multidirectional system:* they are enough flexible and generally suitable for the realization of three-dimensional structures.
- *Prefabricated system:* They are not flexible and mainly designed for use on façades of linear buildings.

It is worth noticing that the naming of the three types is not universally accepted, but varies from country to country. For example *Joint tubes scaffolds* are also called *tube and fitting* in Europe or *tube and coupler* in US. *Multidirectional* are called *prefabricated* in [25], while *prefabricated* are often called *modular scaffolds*. Furthermore, sometimes, *proprietary scaffolds* are also referred as *modular scaffolds*, while *Cuplok* and *ring wedge systems* are examples of *proprietary scaffolds* as quoted in European standards. The scaffoldings used in the analysis are modeled using an Italian producer handbook [22] and the original terminology used in Italy is adopted. However, all dimensions of the models in the paper satisfy the design recommendations of the international standards US OSHA and EN 12811/EN 12812 [23–25].

2.1. Steel scaffoldings with joint tubes

This typology allows working at considerable heights, thanks to the creation of stacked decks, through the connection of steel pipes vertically and horizontally, obtained with preprinted special joints.

The joint tubes scaffoldings are still widely used because they are extremely flexible and allow covering complex façades (e.g. articulated, curved or with drastic changes) thanks to the different types of modules which can be assembled with the tubes (Fig. 2). Joint tubes are also used for the maintenance and restoration of large historical and monumental buildings. They have spread recently in the construction of canopies, shelters, barriers and structures for advertising, trade shows, sporting events, etc. The main structural problem with this type of scaffold comes from the proper installation of the single structural elements, therefore it is extremely important to pay attention to the tube junctions, so that the verticality and/or the inclination envisaged will be maintained to the anchorages and to the supports on the ground.