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Research paper

Problems of monitoring critical elements of scaffolding

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Abstract: Scaffolds are temporary structures that include anchors, elements, and platforms that are used during the construction of steel or concrete structures to support equipment or workers at height. Since these structures have aimed to guarantee safety and support workers at heights, the stability of scaffold systems is of significant importance. These systems have some disadvantages. For example, they are sensitive to vibrations. This feature reduces their stability under service-, cyclic-, or earthquake loadings. Furthermore, the vibrating nature of scaffolds can impose additional axial loads and consequently additional moment loads on the scaffold columns and decrease the safety of workers and increase the accidents of use of them. In this paper, a review of some research has been performed that aimed to solve this problem and improve the stability of scaffolds. These articles have investigated the behaviour of anchors and joints and the influence of imperfections and inaccuracies on scaffolds. A summary of research has been presented that has proposed new methods for predicting the behaviour, damage, and collapse of scaffolds using some structural health monitoring (SHM) methods. Finally, the research gaps and limitations of previous studies have been investigated, with a focus on monitoring and solving the problems of the scaffolds and critical elements so that these problems can be solved and evaluated in future studies.

Keywords: temporary structure, anchor, scaffold, steel, structural health monitoring, prediction

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1. Introduction

Scaffolds are temporary structures that include anchors, elements, and platforms that are used during the construction of steel or concrete structures [1] to support equipment or workers. Since these structures have the purpose of guaranteeing safety and supporting workers at heights, the stability of scaffold systems is significantly important [2]. These systems can be made of different materials, including steel or bamboo [3, 4]. Ensuring the stability of these systems can not only have a beneficial influence on the quality of construction but can also guarantee the life safety of workers and other people near the construction site. In some standards, including Eurocode, there are some regulations regarding the design of temporary structures [5]. In this code, the movements of the soil on which the temporary structure is located should be investigated. Some other characteristics that should be paid attention to in the design of temporary structures are human impact, accident impact (dynamic and static), failure, load-bearing capacity, etc. [5]. In another European standard, some regulations on the use of couplers, baseplates, and spigot pins on scaffolds and falseworks have been presented [6]. In this standard, some requirements have been mentioned concerning the geometric and material properties of the baseplates and coupler elements [6]. In another version of the European Code, some regulations have been presented on different elements of scaffolds and falseworks, including couplers and tubes [7]. To this aim, some details of the design and analysis of these structures have been mentioned, including the slipping and failure force, the stiffness and moment, etc. [7]. Following the types of elements of scaffolds and falseworks mentioned, regulations on special couplers were proposed in the other version of the European Standard [8]. In this standard, some general requirements regarding slipping and failure force, stiffness and moment, etc., have been explained [8]. In another version of the European Standards, some regulations on working towers and mobile access have been presented [9]. These regulations include design, geometrics, material properties, performance, and safety requirements [9]. There are also some regulations on connections, stability equipment, imperfections, design under service, wind, and lateral loads in this code [9]. Temporary works equipment regulations have also been presented in the European Standard. In these codes, some parameters, including material properties, wood element use, protection against corrosion, load-bearing capacity, stiffness, looseness, cyclic load, protection fans, and vibration, have been evaluated [10–14]. The general design and performance requirements of falseworks have been mentioned in European Standards [15]. In this code, the properties of materials, design requirements, connections, and foundations have been considered [15]. Another version of the European Standard presents the regulations for facade scaffolds [16, 17]. In these codes, some regulations on structural design, stiffness, and resistance have been mentioned [16, 17]. In the AISC standard, there are no regulations on the design and execution of scaffoldings [18]. Although some requirements and regulations have been presented to design, analyse, and execute scaffolds and temporary structures, these structures still have many problems that have been mentioned in the following. Therefore, much research has been done to develop scaffolds and their behaviour under different conditions to improve their behaviour, solve their problems, and determine the effective factors in their behaviour. Although there are some effective factors in accidents when using the structures mentioned above (i.e. technical, organisational, and human) [19], the technical ones are significantly important and have caused many accidents in Poland.

Some of these technical problems and their influence on safety have been investigated by Pienko et al. [20]. However, there are also some other limitations. One limitation of these structures is that they are sensitive to vibrating due to the temporary nature of these structures and the placement of the elements that are assembled in them [21]. This feature of scaffolds has caused many accidents around the world and in Poland [21–29]. Another disadvantage of these structures is the probability of damage or corrosion because most of them are made of steel. In a study by Robak et al., the damage and corrosion of more than 100 scaffolds around Poland were evaluated [30]. These systems can be damaged or broken as a result of changing climate, especially during summer, when temperature and sunshine are higher [31]. Some other climate factors can affect workers. In a study by Szer et al., the influence of lighting and illumination on workers was evaluated, and the results showed that these factors can dazzle workers at different times of the day [32].

The above problems affect the elements of scaffoldings (for example, anchors, joints, columns, etc)., and the stability of these structures is reduced. To solve the mentioned problems, improve the stability of the mentioned structures, and monitor or predict scaffold accidents, many studies have been conducted [33, 34]. Some research has focused on evaluating and improving the behaviour of scaffold elements. Some other studies have evaluated inaccuracies and imperfections. Monitoring and predicting the behaviour of scaffolds have also been investigated. In this study, a summary of previous research has been mentioned, and the limitations and problems of monitoring the elements of scaffolds have been investigated. Finally, some possible studies that could be performed in the future have been presented based on the mentioned limitations and research gaps.

2. Anchors

In general, vertical and horizontal loadings can be subjected to any structure, including temporary structures. One of the goals of designing these structures is that their load-bearing capacity should be sufficient to carry such loads. Because they are sensitive to vibration, their vibration can create additional lateral forces, including shear and moment forces, which can injure anchors and bolts [35]. On the other hand, some other factors, including various geometric conditions and imperfections, have caused inappropriate anchor behaviour [36]. The results of the test of the number of 115 scaffolds showed that around a third of them had not completely transferred the vertical load between the walls and the scaffolds, and also some scaffolds did not work properly [36]. This shows that anchors play a significant role in the stability of scaffolds and should also be installed in scaffolds in such a way as to satisfy the stability and proper behaviour of scaffolds because scaffold assembly is controversial. Another possible reason is that this inappropriate behaviour can occur during the operation of the scaffolds. Therefore, monitoring the behaviour of scaffolds during their use is significantly important [36]. Compared to the elements of the buildings (column, beam, etc), anchors and other elements of the scaffolds have greater potential for corrosion and environmental damage because of their temporary nature and exposure to environmental effects directly.

As mentioned above, corrosion can affect anchors and damage them [30]. Occurring damage can decrease the load-bearing capacity of the mentioned systems, and this phenomenon can be a challenge to the anchors. A sample of anchor corrosion is shown in Fig. 1 [30]. Although corrosion and damage can occur on scaffold beams, columns, or surfaces, paying attention to corrosion on anchors or joints is more important because the ultimate capacity of the beams or columns is directly related to the strength of the anchors and joints. In other words, if the joints did not have enough strength, failure of them would cause the beams and columns not to reach their ultimate load capacity. These types of damage will become more important when the non-linear characteristics of the anchors are considered. In conference research done by Jia et al., the non-linear characteristics of the joints in the wheel-coupler formwork support were evaluated while considering the rotational stiffness and load capacity of the joints [37]. The results showed that the joints studied have a higher rotational stiffness under bending and tension than under torsion and bending [37]. Therefore, the joints and anchors in the scaffold structures are significantly important and play an important role in the stability of the above structures.

Fig. 1. Corrosion of the anchor connector on a scaffold [30]

To improve the behaviour of the anchors of the scaffolds, considering the effective parameters is important. Some factors have been found to have a significant influence on joint stability and, consequently, on scaffold stability, including stiffness and material properties [38]. In research by Ilcik et al. [38], some updated finite element models have been developed due to the inaccuracy of the longitudinal and torsional stiffness of the anchor. The results showed that the updated numerical scaffolds have accurate results compared to the FE results. Moreover, models whose anchors have been updated are more stable due to modifying the stiffness of the anchors [38]. The important point is that since the material under real conditions has a non-linear behaviour, considering their non-linear behaviour is important significantly while considering the static behaviour of the anchorages, which can be useful for future studies. Moreover, this paper can be developed considering higher wind loadings and their influences on anchorages because dynamic loading can have many uncertainties.

3. Joints (connections) of temporary structures

Many factors can have a significant influence on the joints of the scaffold, including dynamic and static loadings. In research by Cyniak et al., the influence of natural and free vibrations on the boundary conditions of scaffolds has been investigated and compared with each other. Moreover, different boundary conditions were also evaluated [39]. Joint stiffness is another important parameter in scaffolding. This feature was investigated by Chandrangsu et al. in scaffold joints of two, three, and four ways [40]. The results showed that the vertical bending stiffness is higher and greater than the horizontal stiffness [40]. Most scaffolding joints that have been evaluated in recent years have been considered semi-rigid, and scaffold templates and joints, and fasteners, have also been observed to have a significant impact on the bearing capacity of structures [41]. The results showed that the bearing capacity of scaffolds can be significantly affected by the initial rotational stiffness, and an increase in semi-rigidity can increase the non-linear ultimate load-bearing capacity of scaffolds [41]. Another study on the mechanical properties and failure of steel tube–coupler scaffolding joints (STCS) was conducted by Liu et al. [42]. In this study, four connecting joints were evaluated as shown in Figure 2. The results showed that the sufficient anti-slipping capacity of the joints caused local instability in the vertical steel tube to occur as the main failure mode, while without this capacity, the main failure occurred by fracture and slip of the right angle couplers, and it was observed that the type of upper joint plays a significant role in STCS strength [42].

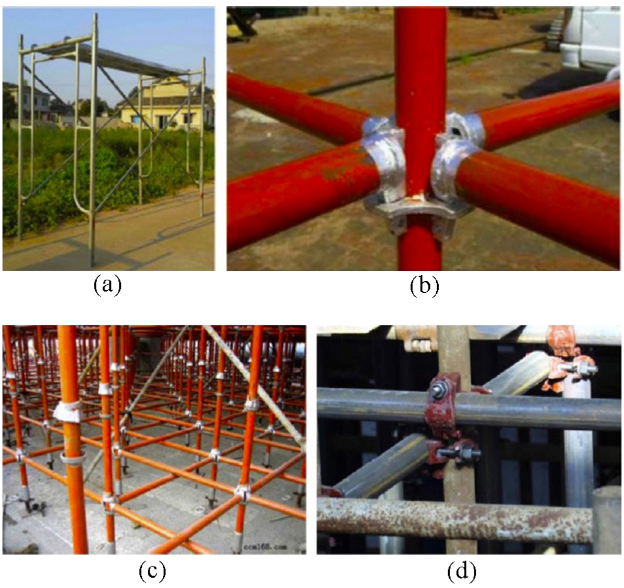

Fig. 2. Types of scaffold joints studied [42]: (a) Doo-type scaffold, (b) Inserting-type scaffold, (c) Cuplock-type scaffold, (d) Steel tube-coupler scaffold

As mentioned above, the joints of the scaffolds and anchors play a significant role in the stability of these systems. The performance and behaviour of the joints and anchors can be evaluated in many aspects including bending stiffness, load-bearing capacity, buckling, moment-rotation behaviour, etc. Some research has focused on mechanical behaviour, including the failure mode of different types of scaffold joints. In a study by Hongbo et al., the performance of mortise–tenon scaffolding structures was investigated [43]. In this study, the vertical and horizontal elements of the scaffolds are connected by the mortise-tenon joints, and their rotational stiffness, shear capacity, and ultimate bearing capacity were compared to the coupler-type scaffolds in which the vertical and horizontal elements are connected by the right-angle couplers. It was observed that, compared to coupler-type scaffold systems, the ultimate bearing capacity of mortise-tenon systems is around 235% higher. Moreover, the rotational stiffness and shear strength of mortise-tenon joints are higher than those of coupler-type scaffolds [43]. In a study by Liu et al., mechanical behaviour, joint stiffness, and imperfections of the plug-pin joint, which belongs to a type of temporary member structure (TMS), were investigated under different loading conditions and displacement was obtained using the vision-based method, and the results showed that this method can monitor displacement with high precision [44]. In this research, different types of plug-pin scaffolds have been investigated, including horizontal bar joint tension (HBT) and horizontal bar joint compressive strength (HBC). The results showed that the initial stiffness of the joints is 40000 kN/m in tension and compression [44]. In recent years, other research has focused on studying the behaviour of joints and anchors of scaffold structures with a socket template [45–47]. In research by Dong et al., the connection joints of a temporary structure have been studied in terms of buckling behaviour and lateral bracing conditions under different geometric conditions of the joints and different loading directions [45]. In this paper, the joints have been made by welding the socket and the template, and the vertical and horizontal elements are connected in the connection zone, which is shown in Fig. 3 [45]. As shown in Fig. 3, the socket was inserted into the template at different depths. The results showed that as this depth increases, the socket fracture has more potential. The braces were located at different angles and it was found that the stability of the scaffold structure increases with increasing angle of the bracing and horizontal element [45]. Finally, the optimal range of vertical diagonal bracing and angle is the 4-step, 2-span (Fig. 4), and 30–70 degrees, respectively, and the lateral bracing was found to increase the behaviour of the system. In the proposed models, the ultimate torsion is 0.6 kN·m with a corresponding rotation of 0.4 rad [45].

Fig. 3. The socket joint of the scaffold [45]

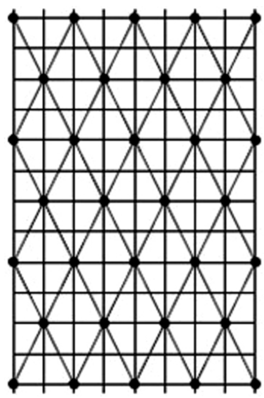

Fig. 4. Optimised diagonal bracing conditions of the scaffold [45]

In another study, Chen et al. evaluated the behaviour of the fastener scaffold under different nonuniform loads, and the values and behaviour of the fasteners under different torsion and moment forces were investigated [48]. In this paper, the influence of imperfections was also evaluated, and the results showed that non-uniform loading conditions decreased the stability of the scaffolds [48]. It was observed that, under non-uniform loading, the scaffold deformation did not increase significantly and after this system was unstable, the deformation increased rapidly. Furthermore, nonuniform load subjected decreased the ultimate load capacity by 45% in the scaffolds [48].

Joints and anchors of the scaffolds are not limited to the beam-column, column-braces, or beam-braces of the scaffolds. The joint of the ground column is also much more important. From the above studies, it can be inferred that an effective way to solve the mentioned problems of these systems is to control the internal forces, moments, and stress in the scaffold elements. As a result of the temporary and vibrational nature and the uncertainty of the reactions of these structures, paying attention to these forces and reactions is much more important. There are many ways to control the mentioned forces. Some researchers have focused on the stress mentioned [49]. One of these has been developed by Błazik-Borowa et al. [50]. Both beam-column joints, anchors, column-ground joints, and all other connections in these structures can develop and affect the internal forces in the scaffolds. Meanwhile, in previous research, the effect of the foundations of scaffolds that have been constructed incorrectly on the static stress of the elements has been investigated [50]. The results confirmed that the use of incorrect boundary conditions on scaffold foundations has increased moment force and this phenomenon has caused an increase in the internal stress on anchors and joints [50]. It can be concluded that uncertainty in the construction of these systems can also have such results, especially if it can have a significant effect on the joints, anchors, boundary conditions, and their internal forces and moments. This shows how important these factors are. In other words, the behaviour of these elements and joints can not only affect the stability of the boundary conditions but also have a significant influence on the whole of the scaffold, especially in its internal forces and stress. However, the mentioned research focused on the static behaviour of the incorrect foundations, and the dynamic behaviour should be studied while considering the soil-scaffold interaction.

Another critical element of the scaffolding is the columns and ground joints. Very little research has focused on this matter maybe because these systems are temporary, and considering a fixed restraint at the bottom of the columns could not be possible in such a way as is considered in steel or concrete structures. Therefore, the mentioned joints can be implemented and considered for temporary use. Therefore, significant vibrations can be created when workers work on scaffolds. To solve this problem, the following approaches can be performed. Vibrating scaffold columns due to the temporary column-ground joint may create uncertainty. If the joint between the column and the soil is considered to be fixed and restrained, the uncertain and non-linear behaviour of the soil would be the next problem. Because when the vibration load or even service loads are applied to the columns of the scaffolds and then to the soil, the response of the soil should be considered in terms of displacement, load, etc. The other characteristic of the soil to which attention must be paid is the level of damping of the soil. In research by Markou et al., the nonlinear interaction between soil and the pile of offshore wind turbines has been evaluated [51]. In this research, the damping level of the soil has been studied considering the influence of dynamic load and harmonic excitations on the non-linear response of the soil.

4. Stability of the structure

Since scaffolds are sensitive to vibration, this can be one of the reasons for the unstable behaviour of these structures under service and earthquake loads. This feature can also prevent the elements of the scaffolds from reaching their ultimate load capacity. Therefore, optimising the design of the mentioned systems can be prevented. To solve this problem, force limiters have been introduced by Lenar et al. [52]. This element redistributes the loads and forces of the structural elements of the scaffolds to the adjacent elements when the limit value of the force in the elements is reached. As a result, the force in the elements is reduced and the stability of the system is improved [52].

To improve the stability of such structures, another solution is to use the bracing system in such systems [53] and consider eccentric loads [54]. Because these structures are temporary and the service and lateral loads can be subjected to the system and then developed in a variety of directions, paying attention to the eccentric loads is so important. Some research has focused on eccentric loading [46]. To solve this problem, some bracing systems have recently been developed.

The lateral and vertical performance of the temporary structures was evaluated by Liu et al. [55]. In this paper, the distribution of strain, failure mode, and ultimate load-bearing capacity of the models was investigated in different vertical loads, lateral bracing conditions, and different spans. The results showed that an increase in the vertical load changed the failure mode under horizontal load from general overturn to buckling of the diagonal brace and, in the next step, to buckling of the upright rod. The failure mode of the model under a vertical load of 360 kN is shown in Fig. 5. The results also showed that the horizontal load can make a change in the lateral stiffness in such a way that exceeding this load from 16 kN significantly decreases the lateral stiffness. It was also observed that the maximum lateral capacity of the models can be reached when the vertical load subjected to the model is about 53% of its ultimate vertical load, and an increase in the vertical load of more than 85% of the ultimate load significantly reduced the lateral capacity. Furthermore, the importance of diagonal bracing in the lateral behaviour of temporary structures cannot be neglected. The failure mode of the models after braces removal is shown in Figure 6. In this investigation, the top and bottom bracings were removed and the behaviour of the scaffolds was evaluated after the braces were removed. It is illustrated that when the top braces (second story) or bottom braces (first story) are removed, the scaffold columns buckle. Finally, a formula was proposed to predict the ultimate lateral load capacity of the models based on the evaluated data [55].

One of the solutions to increase the stability of the scaffolds is temporary bracing in prefabricated structures, including the scaffolds [56]. One of the factors that can affect the stability of scaffolds is creating vibrations as a result of dynamic loadings in such structures. Since these structures are temporary, the dynamic loadings to which they are subjected are completely different from those subjected to a concrete or steel building. When workers walk on scaffolds, vibration is induced in these systems and the frequency depends on the characteristics of the walk. The dynamic loading that can be subjected to these structures is not limited to the vibration caused by walking. Dynamic wind loading can also affect the mentioned systems [57, 58]. Investigating the wind load in these systems can be carried out in either dynamic or static cases. The static wind load has been evaluated in a study by Lipecki

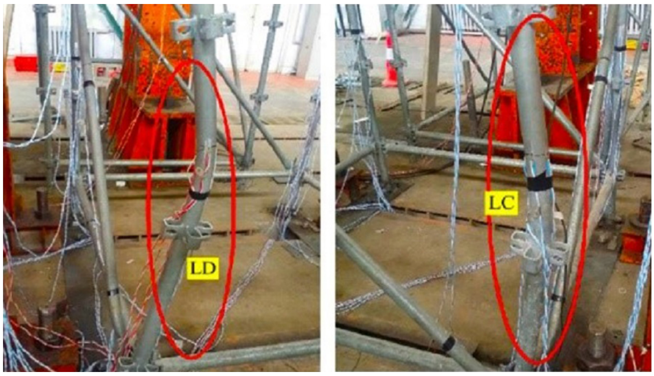

Fig. 5. The failure mode of the model under vertical load of 360 kN [55]

(a) (b)

Fig. 6. The failure mode of the model while bracings have been removed [55]: (a) Removing the top bracing, (b) Removing the bottom bracing

et al. in which it was observed that the wind load can increase the axial force and normal stress in the elements of the scaffolds in such a way that even its maximum load capacity is exceeded [59]. Therefore, in future studies, the dynamic or static effect of wind in different types of joint scaffolds can be studied. It is worth mentioning that the studies that have been performed on the performance and behaviour of different types of scaffold joints and anchors are discussed in the following. However, many researchers have investigated the dynamic behaviour and vibration of scaffolds [60, 61].

In a study by Błazik-Borowa et al. [21], dynamic loadings that are subjected to the mentioned systems have been considered at different frequencies, and prediction models were proposed. It was observed that an increase in the number of braces and a decrease in the length of the anchors can increase the natural frequency of the systems and, consequently, improve safety. In addition to dynamic loads, the stability of scaffolding systems can be significantly affected by static loads. In other words, when workers walk on scaffolds, this can have both dynamic and static effects on these systems. Moreover, the weight of equipment and elements, which are called service loads, should be considered effective parameters of the above structures. Błazik-Borowa used a method to present the probability density functions of scaffolds in which the probability of scaffold damage was predicted considering the maximum load of the vertical module and scaffolding platform. The results illustrated that in Poland there has been a high probable risk of exceeding the service load from its allowable limit [62]. In another research, the harmonic excitation of scaffolds under dynamic loading was evaluated [63]. In the study mentioned, after analysing the mode shapes under natural frequencies of the scaffold structure, the maximum displacement was determined at selected points. The results showed that low excitations close to the natural frequency of the structure affect large areas of the scaffolds [63]. In the study by Peng et al., the stability behaviour of the scaffolds with inclined surfaces and an extended jack base was evaluated and the failure mode, the maximum load capacity, and the deformation of the scaffolds were analysed after loading [33].

5. Inaccuracies and imperfections

In addition to static or dynamic loads, scaffolding can be affected by other factors that make these systems unstable, including imperfections [64, 65]. The instability of the scaffolds can lead them to collapse. In research by Crosti et al., some factors, including lack of adoption of building codes, inadequate structural design, and imperfection in construction, have been found to have significant influences on the stability and collapse of temporary structures and other structures [66]. In this article, the anchor between the column and the ground has been mentioned as the key element in temporary structures [66]. The effect of each of the mentioned parameters has been considered in some other papers, and each factor can have a separate influence on scaffolding systems.

As mentioned, one of the factors is the constructional imperfections. Baek et al. proposed a framework to verify the adequacy of scaffold installations [67]. In this framework, the safety level of scaffolds can be identified without visiting scaffolds on-site [67].

Because scaffold systems are temporary, imperfections in their elements and anchors can significantly decrease their stability and impose additional bending [2]. This can cause an excess of the axial or flexural load from its allowable limits. The geodesic inventory method for 120 scaffolds has been developed by Błazik-Borowa et al. [2], and it was found that constructional imperfections can cause an increase in deviation of up to 400 mm in the elements and 1.3 degrees in the joints of the scaffolds. The reason for this deviation may be mainly related to imperfections in the joints. Therefore, joints in scaffolds are significant and should be considered. Another aspect of imperfections, including their configuration and dimensions and the effects on the static capacity of the façade scaffolds, was evaluated by Błazik-Borowa et al. [68]. In this paper, the imperfection in the structure was considered in two ways. First, a certain part of the scaffold platform was moved so that a distance of δ was created between the node levels (Fig. 7). Second, the first buckling form was considered to be subject to imperfections. The structure was analysed under nonlinear static conditions; the material properties were defined as linear [68]. The mentioned imperfections were considered in three separate loading conditions, including two horizontal loadings, which are perpendicular, and one vertical loading condition (Fig. 8) [68]. The results showed that the components of the scaffold can be negatively affected so that internal forces can increase in the frames and supports, and this stress in the lower layers of the scaffold is greater than in the upper layers [50].

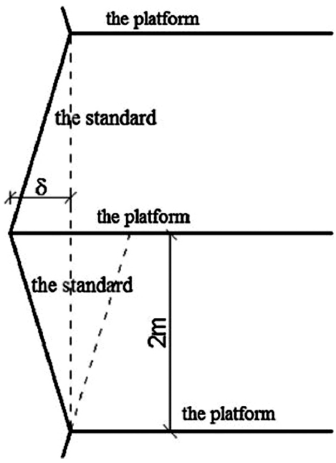

Fig. 7. The first method of considering imperfections – shifting the platform [68]

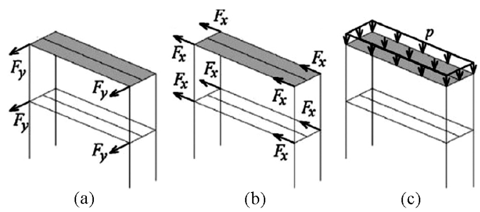

Fig. 8. Loading conditions: (a, b) Horizontal, (c) Vertica [50]

In another research, inventory survey methods have been used to evaluate facade scaffolds [69]. In this study, total station and photogrammetry approaches have been used. Then the tests and surveying methods were obtained, analysed, and compared with each other. The results showed that the methods studied are accurate to 3 mm and 3.6 mm for width and height, respectively [69]. Parameters such as out-of-plumb deflection, out-of-straightness, and load eccentricity have been applied for the accuracies mentioned [69]. In future studies, two ways can be followed: First, other factors can also be considered and obtained using the mentioned methods. The test results can also be compared with approximate and numerical methods. Secondly, since the methods studied take so much time and can be inaccurate due to human error [69], the behaviour of the façade scaffolds can be evaluated and predicted using structural health monitoring (SHM) methods, and the results can be compared with the analysis and approximate methods.

6. Elements constituting health and safety protection

Artificial intelligence and structural health monitoring have various applications in predicting behaviour and different parameters in every engineering structure. For example, many studies have been conducted on evaluating the influences of material and architectural design, construction and building management, smart operation, etc. on structures by using machine learning, deep learning, and artificial intelligence [70,71]. Different techniques are used in these methods.

For example, in another research, Light Gradient Boosted Trees, Keras Deep Neural Networks, and Extreme Gradient Boosted Trees algorithms have been used to predict the maximum moment load capacity of FRP-reinforced beams [72]. These methods can be used to predict the behaviour of the structural elements and scaffolds to solve their technical problems and improve their behaviour, especially in the case that these elements have uncertainties in their properties.

As mentioned above, scaffolding systems have a lot of uncertainty due to vibration and their temporary nature. Therefore, the importance of predicting their behaviour under different loading conditions and observing their behaviour is significantly important. To this aim, some research has been done to propose predictive methods. Kim et al. proposed a method to verify regulations related to scaffold safety using the Terrestrial Laser Scanning (TLS) method [73]. Błazik-Borowa et al. proposed another method to present the probable failure of the scaffolds considering some effective parameters, including geometric imperfections, anchors, damage, and ground-bearing capacity [74].

Another approach is to predict and detect scaffold damage before it occurs and to monitor structural health. Zhen-yu et al. recently proposed a new damage detection method in which digital images of scaffold vibration were collected and processed [75]. The proposed model was used to discuss the 10 experimental scaffolds and the results showed accurate damage detection in these systems [75]. Fig. 9 shows good accuracy between the natural vibration frequency and the velocity of the camera and accelerator results [75]. This method can be developed for many scaffold structures under various conditions.

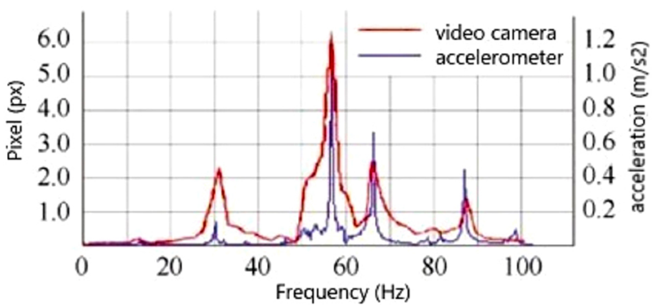

Fig. 9. Comparison of the results of the spectrum analysis and the frequency of the camera (red) and accelerator (blue) [75]

Another method is to monitor structural health and predict and detect damage in the elements in structural health monitoring (SHM). To this aim, various methods can be used. In a study, machine learning has been used to assess the scaffold work surface and monitor and predict its behaviour using the Activity Analysis method to make human supervision on scaffolds easier and faster [76]. In this approach, some pictures of scaffolds were taken with video cameras, and then the data were analysed using the machine learning approach and the behaviour of the workface and joints was evaluated and monitored [76]. Another method of Machine Learning (ML), called the Support Vector Machine (SVM), has been used to predict failure and classify various cases of scaffold failure [77].

In the SHM method, some sensors can be installed on the elements to detect damage to them. Some similar methods have been conducted in recent years to monitor the scaffolds. One of them has been proposed by Wang et al. [7]. In this paper, the detection of looseness in the joint of the cup-lock scaffolding was performed using the percussion-based approach. This method has been conducted using the Mel frequency cepstral coefficient (MFCC) and the convolutional bidirectional long- and short-term memory (CBLSTM) method. In this method, the sound signals from the mentioned joint, shown in Fig. 10, were extracted by subjecting the percussion to the joint [78]. The data was then collected and trained using the convolutional neural network (CNN) approach. As shown in Fig. 10, percussion was applied to the joint and damage detection was obtained using the sound signals of the percussion method. In the paper, this method has been mentioned to have no disadvantages over the SHM method for the installation of sensors on the elements [78]. Although this method does not require the installation of such sensors, three points are challenging. First, in the percussion-based approach, the percussion was applied to the joint in situ and on the construction site. Therefore, this act becomes more challenging when percussion is supposed to be applied to a large-scale or high-height scaffold. Now, the question is how it is possible to apply percussion at heights and who will guarantee human safety in an area that is difficult to reach. The application of this percussion by a human can be more dangerous than installing sensors and even working the workers at heights. Therefore, this method does not have advantages compared to the SHM approaches and a decision on this should be made with caution. Second, it is observed that in the percussion-based method, percussion is applied to the joint to detect damage. This means that if columns, beams, or other structural elements are supposed to be detected in terms of damage, various percussions should be applied to them. Thus, this can be more challenging when considering a large-scale scaffold with numerous elements and joints. Third, this method has been developed using previous data sets and can be applied to predict overall damage to the scaffold system. Meanwhile, sensors in the SHM methods can be installed at any point in the structure and can detect failure or damage at any point. This shows that not only does the percussion method have no advantages compared to the SHM methods, but the SHM methods can also have greater accuracy in detecting damage and corrosion, and this is necessary for such structures to detect damage at every point of the structure. Therefore, SHM methods are still necessary and useful, especially in the case that there is still very little research that has focused on predicting the damage of scaffoldings using SHM methods. There are many ways to detect damage, corrosion, failure, deformation, etc. from scaffolds, and this method can be performed wirelessly [79].

In recent years, various methods and algorithms have been developed to monitor the situation of scaffolds. Some of this research has investigated the behaviour of scaffolds using IMU and EMG sensors based on the ANN method [80]. In another approach, a robot dog was used to monitor the scaffold and obtain the structure information and point clouds of the elements, analyse the information using deep learning algorithms, and present the 3D map to reconstruct it [81]. Data analysis and laser scanning were performed using the LIO-SAM approach and the results showed accurate maps [81]. This research also has some limitations such as the following. First, this method has been mentioned in the article that it has some limitations in performing at higher heights [81]. To solve this problem, some other models, including bird robots, for example, can be used to fly and obtain information on scaffolds with higher heights. Second, instead of algorithms to reconstruct scaffolds, some other algorithms can also be given to the robot to monitor and detect damage, force, stress, or deformation and predict them. In other words, instead of the sensors that are installed on the scaffold structures, these sensors can be given to the robot, similar to the sensors that are given to the robot dog, and the collected data can be analysed by the proposed robot. This can reduce the cost of installing SHM sensors and can also increase accuracy. On the other hand, the robot dog monitors the behaviour of the scaffolds by scanning, and data are processed using machine learning methods. Therefore, this method is more affordable and cheaper than human monitoring [81]. These methods can be done automatically, with software and robots, and these methods can be used to monitor many scaffolds and structures and maintain them. However, monitoring scaffolds by humans requires time, workers, equipment, etc., which will be expensive, especially in large scaffolds with various elements [81, 82]. The robot dog schematic is shown in Fig. 11 [81].

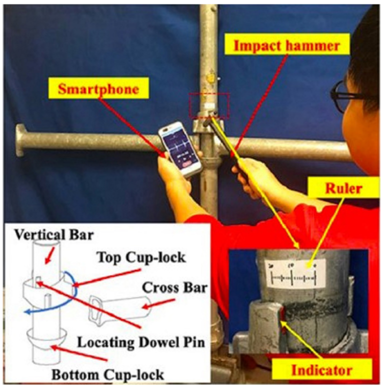

Fig. 10. Experimental setup and percussion subjected to the joint [78]

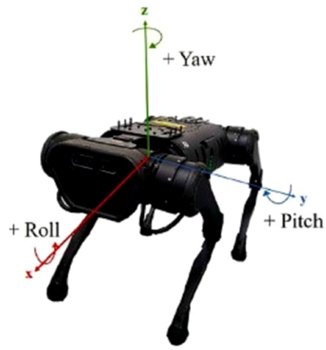

Fig. 11. Robot Dog [81]

A method was proposed to measure the motion similarity of 2 mobile devices to recognise the latching state of the safety hook [83]. In this method, the rotation and acceleration of a body, and a hook, have been used to represent the motions [83]. Consistent with the mentioned research, another research also focused on monitoring the deformation of scaffolds according to the multithread LiDAR point cloud method, and the results showed that monitoring the deformation of scaffolds can be carried out daily and with a sufficiently accurate [84]. Another method to monitor the damage and failure of scaffold structures was performed by Liang et al. using the Eulerian video magnification method, and the results showed good consistency with the experimental conditions [85].

7. Research gaps and future studies

Although much research has been carried out to improve the behaviour of scaffolds, which have reduced the number of accidents and saved many lives, especially in Poland, there are still many research gaps that should be paid attention to. Some of these research gaps have been found in two important fields: a) the static behaviour of scaffolds and b) the anchorages of scaffolds. The research that has been done so far could not solve many important problems regarding the static operation of scaffolds and anchorages under different geometric, material properties and, especially, loading conditions. This is because, in scaffolds, uncertainty is very important, significantly due to the vibration nature of these structures. In addition, there are still many unanswered questions regarding the choice of optimal and stable scaffolds and anchorages. Moreover, there are still various conditions in terms of loading, anchorage, material properties, etc, that need to be studied comprehensively. One of the reasons for this gap may be related to the lack of comprehensive regulation regarding the design of scaffolds and the effectively mentioned parameters.

From the review of previous research, it was observed that some research gaps need to be considered, which are mentioned below. It was found that imperfection and a variety of geometric conditions in the scaffolds, in addition to the vibrating and unstable behaviour of the scaffolds, have caused inappropriate behaviour of the anchors. There is very little research on monitoring the status of anchors under static and dynamic loads. Furthermore, the problematic nature of conducting surveys directly on construction sites is of significant importance.

In addition, some research has been done to improve the stability of the scaffolds. However, there are some ways each of them can be improved in the future, which are mentioned below.

1. In some studies, the material properties of the scaffolds were investigated. In most of them, the material properties were assumed to be linear. But the important point is that since the material in the real conditions has a non-linear behaviour, considering their non-linear behaviour is important significantly while considering the static behaviour of the anchorages, which can be useful for future studies.
2. Moreover, this paper can be developed considering the higher wind loadings and their influences on the anchorages because dynamic loading can have a lot of uncertainties. From the above studies, it can be inferred that an effective way to solve the mentioned problems of these systems is by examining how the internal forces, moments, and stress in the scaffold elements will be controlled. Due to the temporary and vibrational nature and the uncertainty of the reactions of these structures, paying attention to these forces and reactions is much more important. There are many ways to control the mentioned forces.
3. These internal forces and stress can be created as a result of static or dynamic loads. Therefore, the wind or earthquake load can be analysed dynamically or statically. In other words, following research on the behaviour of scaffolds under wind loads, these loads can be analysed and subjected to static or dynamic loads. For another example, earthquake loading has a dynamic nature but can be analysed in software in the form of static or dynamic. When the earthquake load is considered static, this load can be estimated based on the seismic coefficient and the weight of the structure. Then, this load is applied horizontally to the base of the building. However, when this load is considered dynamic, it is estimated as an impact load and the value of the earthquake force is not constant during the earthquake time.

   Therefore, it can be useful to consider the influence of the wind and earthquake on the scaffold statically and dynamically and to compare these two ways with each other, and in our research, static behaviour can be chosen. In future studies, the interaction between the joint of the soil and the scaffold column structure can also be evaluated to determine the vibration response and the nonlinear behaviour of the soil and reduce the vibration. As mentioned in this paper, vibration can imply additional forces on the columns. As a result, these elements are prone to buckle. In addition, the influence of this force on the non-linear behaviour and damping of the soil should be evaluated in future studies.

4. Although some studies have been done on different types of scaffolds, there are still many other types of scaffolds (for example, door-type, inserting-type, cup lock-type, or steel tube-coupler scaffolds) that can be investigated in terms of static or dynamic loading.
5. In recent years, anchors have been found to have a significant influence on the internal forces and stability of scaffolds. However, a variety of methods have been developed to monitor the failure, deformation, etc. of these structures. Some of these are contact sensors and others are remote ones. From the above sentences (Section 3), it was observed that there is still a great research gap to evaluate the static behaviour of the scaffolds under static loadings. Therefore, in future studies, the behaviour of the scaffolds can be investigated while focusing on the static loadings (including wind, earthquake, or service loads) and the behaviour of the anchors, and then the failure, deformation, etc. can be monitored using the SHM methods.
6. It was observed that there are limited studies investigating the behaviour of the scaffold with a focus on different types of materials (i.e., concrete, brick, etc.), and this can be evaluated in future studies.

8. Conclusions

This study aimed to present a review of previous research on the problems of critical elements of scaffolds and proposed solutions. Furthermore, in this research, the important results were highlighted, and the limitations of previous research were also discussed with caution.

In this paper, first, problems with anchors and joints of scaffolds were reviewed and investigated. Then, the influences of the effective parameters on the stability of the scaffold elements were investigated. In the next step, the influences of inaccuracies and imperfections on the stability and behaviour of the scaffolds and the critical elements were reviewed and investigated. Finally, some research that had proposed solutions to monitor scaffolds and protect the health and safety of scaffolds and people was investigated.

One of the strengths of this research is that it investigated and discussed the strengths and limitations of previous studies. This article highlights the importance of the effective factors on the behaviour of the scaffolds and provides insight for future research fields. The findings of this study have significant implications for understanding how this research field can be developed in the future, how important scaffolding problems have been solved and what factors depend on the stability, behaviour, and load-bearing capacity of scaffolds. This paper provides one of the first comprehensive investigations and reviews of the problems of critical elements of scaffolds and their effects on the behaviour of scaffolds. This paper also shows the importance of working in this growing research field. In summary, some factors that can affect scaffold elements are mentioned in Table 1.

Table 1. Parameters that can damage the scaffolds

Factors and elements that were investigated	Investigated parameters that can affect the scaffolds
Anchor	Vibration, corrosion, stiffness, material property, load-bearing capacity, anchor length
Joint	Natural and free vibrations, boundary conditions, joint stiffness, shear capacity, different types of joints (socket-template, plug-pin, cup-lock, tube-coupler, inserting type), bracing in the scaffolds, non-uniform loads, boundary condition of scaffold foundation, damping level of soil
Stability	Service and earthquake loads, removal of the bracing system, strain distribution, failure mode, load-bearing capacity, different vertical loads, horizontal load and its effect on lateral stiffness, vibration caused by dynamic load, static wind load, different frequencies of dynamic loads, static loads,
Inaccuracies and imperfections	Lack of adoption of building codes, insufficient structural design, imperfections in construction, anchor between column and ground, axial and flexural loads, the effect of configuration and dimension of imperfection on the static capacity of facade scaffolds.
Health and Safety Protection	Predicting and monitoring the behaviour of scaffolds and joints using machine learning and deep learning methods, predicting maximum load capacity of the scaffolds, detecting damage in the scaffolds before it occurs, using the Activity Analysis method to predict the behaviour of the scaffolds and analysing the pictures of the scaffolds, installing contact or remote sensors to monitor the health of the scaffolds (SHM method).

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Problemy monitorowania elementów krytycznych rusztowania

Słowa kluczowe: konstrukcje tymczasowe, zakotwienie, rusztowania, konstrukcje stalowe, monitorowanie stanu technicznego konstrukcji, prognozowanie

Streszczenie:

Rusztowania to konstrukcje tymczasowe. Składają się ze stojaków, prętów stężeń, podestów i zakotwienia. Najczęściej są one wykorzystywane na etapie budowy czy remontu konstrukcji budowlanych i służą do podtrzymywania sprzętu i pracowników na wysokości. Ponieważ konstrukcje te mają na celu zagwarantowanie bezpieczeństwa ludzi pracujących na wysokości to olbrzymie znaczenie ma ich stateczność. Rusztowania mają różne wady np. są wrażliwe na wibracje. Ta cecha zmniejsza ich stabilność pod działaniem obciążeń zmiennych, cyklicznych lub trzęsieniem ziemi. Co więcej, drgania rusztowań mogą powodować dodatkowe siły osiowe i momenty zginające w słupach rusztowania, zmniejszając bezpieczeństwo pracowników i zwiększając liczbę wypadków związanych z ich użytkowaniem. W niniejszym artykule dokonano przeglądu badań mających na celu rozwiązanie tego problemu i poprawę stabilności rusztowań. Analizowana w pracy literatura dotyczyła zachowania kotew i złączy oraz wpływu imperfekcji geometrycznych i niedokładności montażowych na bezpieczeństwo rusztowań. W artykule przedstawiono podsumowanie badań, w których zaproponowano nowe metody przewidywania zachowania, uszkodzeń i katastrof rusztowań przy użyciu metod monitorowania stanu konstrukcji (SHM). Wskazano luki badawcze i ograniczenia poprzednich badań. Skoncentrowano się na monitorowaniu i rozwiązywaniu problemów rusztowań i ich elementów krytycznych, tak aby mogły być one rozwiązywane i oceniane w przyszłych badaniach.

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