

DESIGN BASIS OF MOVABLE SCAFFOLDING SYSTEMS FOLLOWING AMERICAN AND EUROPEAN CODE PROVISIONS AND RECOMMENDATIONS

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Abstract. Construction of bridges span-by-span with Movable Scaffolding Systems (MSSs) is a very efficient and competitive technology. Normally used for spans between 25 and 70m, the technology has allowed reaching longer spans due to technological advances, specifically in bridge construction equipment. Thereby, the use of MSS has become widespread and well-accepted in a large number of locations across the USA and Europe. Nevertheless, despite its extended application, there is no single specific code provision that can explain, control, and give recommendations about all aspects of MSS during its design and usage. On the contrary, the information is spread over several documents. This paper aims at bridging this gap by providing an extensive review of code provisions and recommendations that can be valid for the MSS design. Applicability of these documents is discussed by analysing loads, safety factors, load combinations, limit states, as well as structural analysis and design. After this, a proposal of a design basis for MSS is presented for each aspect mentioned following provisions and recommendations of the considered codes.

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Introduction

The Movable Scaffolding Systems (MSSs) are an in-situ full span casting method of concrete bridge decks. This technique implies that during construction, the bridge superstructure is carried by an external formwork mounted on the launching girders. The girders are supported by either pier supports or a cantilever rear support and a pier support. MSS was used for the first time in 1961 in the construction of the Krahnember Bridge in Germany designed by Hans Wittfoht (Leonhardt, 1984). Since then, during the 1960s and 1970s, the technology was developing in many aspects and expanded to different countries. At the beginning of the twenty-first century, a new generation of MSSs has appeared, which implies application of the organic prestressing system (OPS) (Pacheco, 2008; Pacheco et al., 2007). In the most recent developments, MSS technology has proved suitable and efficient for in-situ span-by-span deck erection of multi-span viaducts, offering such benefits as safe construction, simple geometric control, reduced material consumption, and a beneficial impact on sustainability (Pacheco et al., 2020).

Despite evolution of MSSs, the complexity of their use can pose considerable risks, since such factors as different load conditions, typology of supports, technology, and behaviour, as well as local bridge construction specifics all over the world should be accounted for. Disregard of these variables may result in problems in terms of quality, safety, and durability, and ultimately lead to accidents, such as the collapse of the MSS (Hingorani & Tanner, 2020; Rosignoli, 2007; Tanner & Hingorani, 2013). The situation may be improved if a correct set of provisions or codes is adopted, mainly addressing two aspects: design, covering the issues associated with the fabrication of MSSs, and construction, which would cover all issues concerning their usage. To the best of authors knowledge, these problems have been neglected thus far.

The actual standardized design criteria in the US and Europe provide some recommendations with regard to the use of some bridge construction equipment, but the information is limited, and, in some cases, the recommendations cannot be considered as official code provisions (Confederación Nacional de la Construcción, 2015). Furthermore, the rules expressed in the codes cannot be applied in design of MSSs, because of the specific conditions, their complex behaviour, usage, and high-risk level during their construction (André

et al., 2012). Design criteria for a permanent structure cannot be the same for bridge construction equipment, they may not be applied to the temporary works either.

In this regard, the existing information laid down in code provisions and recommendations from the US and Europe concerning the behaviour and use of MSSs was analysed in order to develop proposals for establishing a design basis that can become a valid guide in both continents. This analysis considers common understanding of the functioning of MSSs to enable discussion of dissimilar aspects of MSS design basis. For the reader's convenience, further information can be found in (Confederación Nacional de la Construcción, 2015; Members of IABSE WG 6, 2018; Rosignoli, 2013). Future research on this topic can facilitate development of a forthcoming official document for MSSs and, thus, help establish a control mechanism of MSS design and usage conditions.

The paper is divided into two parts – first, the available code provisions and recommendations in use in the USA and Europe are reviewed, second, proposals with regard to the design basis for MSSs are made on their bases. Every aspect of a possible standardized design is analysed considering the available data and then proposals are made for each parameter. The paper is organized as follows: After the introduction, there is a review of the application fields of MSSs considering the requirements and limitations thereof. Next, details about the structural behaviour of MSSs during their assembly, functioning, and dismantling are discussed. Afterwards, the existing documentation is discussed and analysed, then design basis proposals are made considering the following parameters: loads, safety factors, load combinations, and limit states. Some ideas about the structural analysis and design are discussed in more detail. Finally, the conclusions and the scope of future research are presented.

1. Fields of application of MSSs

The main application of MSSs is related to the construction of bridges, the span lengths of which have mainly ranged between 25 m and 70 m (Members of IABSE WG 6, 2018) with an exception of the Ahrtal Bridge in Germany built with a span of 108 m (Majewski, 1976). Nevertheless, the OPS enabled MSSs to reach span lengths up to 90 m (Pacheco et al., 2020). Many reasons make MSSs the preferable option in building a multi-span bridge. According to different authors (Däbritz, 2011; Díaz de Terán et al., 2016; Pacheco et al., 2020; Rosignoli, 2013), MSSs are a suitable construction method for several reasons mentioned below.

Regarding the design of the bridge, application of MSSs allows adopting a simpler deck design with a lower need for post-tensioning, which would result in reduced material consumption. Regarding the construction of the bridge, MSSs allow for a simpler geometric control, ensure higher safety in construction, require lower manpower, which results in cost-effective production and reduction of facility requirements. Regarding the location or special demands, application of MSSs is advisable when there are high architectural requirements and difficult topography. Nonetheless, MSSs also have certain disadvantages and limitations (Pacheco et al., 2020; Rosignoli, 2013), such as the cost of shipping, assembly, and dismantling, high level of technology required, possible weight of the MSS that can have an impact on the design of the bridge, the speed of construction compared to other techniques, and the limited span length. In addition, MSSs can be also used for other applications, such as the overhaul and demolition of bridges (Däbritz & Mertinaschk, 2018). The design basis developed in this paper is based on the assumption that the principal function of MSSs is construction of bridges.

2. General aspects of MSS behaviour

2.1. Stationary Stage

This stage includes all works needed to construct a bridge span. The stationary stage is the phase when the MSS does not move having a cantilever suspension at the back as its supports (at $L/4$ or $L/5$, L is the bridge span length) and a pier support at the front. In this position, after the correct geometry and pre-camber have been checked in both main girders and formwork of the MSS, the reinforcement of the bridge deck must be placed into the formwork. Afterwards, fresh concrete is cast depending on the pouring phases or timetables planned. Then, when it has obtained sufficient resistance to resist the prestressing load, the prestressing works start. Finally, when the deck is completed, the MSS can change its cantilever support for the pier support. This is the conventional work sequence to build a bridge deck; however, there can be other intermediate steps depending on the bridge configuration, for example, two pouring stages of a box beam: first the U-section is cast and then the top slab (Díaz De Terán, 2013).

2.2. Launching Stage

The launching stage includes all configurations from the position where the MSS leaves the cantilever suspension to the next span position before it leaves the pier support. Accordingly, different configurations depend on the launching system and the numbers of supports of the MSS. The launching system defines the speed, number of supports, type of movement, and other aspects that can affect this stage. Furthermore, this stage can also include possible vertical and transversal movements that may be needed to correct deflection and to adjust the MSS on the supports, respectively. During this stage, it is recommended not to allow workers on an MSS to avoid any additional loads. Normally it concerns not only a launching system but also a braking system to avoid any accidents either because of the capacity or the instabilities that can be present. Thereby, it is important to study all possible geometrical configurations.

3. Existing design documents and proposal

The following aspects of different standards are discussed following the Load Resistance Factor Design (LRFD) philosophy and principles.

3.1. Loads

3.1.1. Permanent loads

The MSS is composed of the launching girders, the formwork supporting the structure, the formwork, and supporting and moving devices (Däbritz, 2011). Thus, the relative disposition of the launching girders with respect to the bridge superstructure allows distinguishing different types of MSSs: overhead, underslung, and underslung-alongside. The launching girders are the principal structural elements that carry loads before they are transmitted to the supports. Therefore, the weight of the launching girders is considered self-weight and the other elements of the MSS and the elements necessary during construction, such as stairs, walkways, handrails, and others, are considered dead loads.

The launching girders are normally box girders or truss girders made of steel (Members of IABSE WG 6, 2018). Nevertheless, in some cases, to reach longer spans, these girders can present a bowstring configuration (Pacheco et al., 2020). In both situations, the structure can include the

OPS as part of the structure acting during the stationary stage. The self-weight of a launching girder may range between 9 kN/m and 32 kN/m according to (Members of IABSE WG 6, 2018).

The formwork can be made of timber or steel, while the formwork supporting the structure is normally composed of steel members. Thereby, the resultant load depends on the geometry of different structures and their specific weight. On the other hand, such auxiliary structures as stairs, walkways, handrails, and others are made of aluminium or steel.

In all cases, the permanent load depends on the geometrical properties and the specific weight. Therefore, it is important to consider all elements of the MSS. The values recommended for metals and steel in EN 1991-1-1 (European Committee for Standardization (CEN), 2019b) can be adopted as a reference in the case of Europe and ASCE/SEI 7-16 (American Society of Civil Engineers, 2017) – in the case of the USA.

Since the proposal is related to the specific weight of each material, it is advised to follow the recommendations for the location where it will be used. The geometrical properties depend on the elements used. Strict measurement of the self-weight considering the materials used in the joints of the elements and modules is recommended. Special considerations regarding the application of the permanent loads in the launching girders should be the possible eccentricities of loads respect to their centre of gravity of the elements, and the type of joints used between elements. Furthermore, possible geometrical imperfections due to the stiffness of the elements or the assembling of the structure must be considered either by a second-order analysis or strict control of the limits of those imperfections.

3.1.2. Construction loads

The principal construction loads related to MSSs are the following: working personnel, equipment, storage of materials, and fresh concrete.

3.1.2.1. Working personnel

The impact of the personnel depends on the concrete phase of the MSS use. During the stationary stage, the working personnel plays a more important role than during the launching stage, where it is preferable not to have workers on the structure. The American code provision ASCE/SEI 37-14 (American Society of Civil Engineers, 2015) recommends values for the working personnel according to the number of the workers, setting a minimum value of 1.11 kN per each one with a maximum distance of 457 mm between the workers. This value is a concentrated load and can be distributed if the specific area

is known. The same value is recommended by the AASHTO standards for both bridges and temporary works (American Association of State Highway and Transportation Officials (AASHTO), 2017b, 2017a). On the other hand, EN 1991-1-6 (European Committee for Standardization (CEN), 2018c) recommends an area load of 1 kN/m^2 in all walkways and work areas, including the working personnel and hand-tools. This is the principal Eurocode used as a reference for construction loads. However, some European codes can be more suitable in specifying this load considering the type of structure. EN 12812 (European Committee for Standardization (CEN), 2008), which is the code for falseworks, recommends a minimum area load of 0.75 kN/m^2 , but it specifies that this value depends on the type of work, hence it can be higher. In order to get a more precise breakdown of this value, this last code references EN 12811-1 (European Committee for Standardization (CEN), 2005), which is the code for scaffolds. In this code, there are six classes of loads where 0.75 kN/m^2 is the lowest one corresponding to Class 1. The parameters considered ascribing these classes include the working personnel, hand-tools, and some minor equipment. Additionally, EN 180201 (European Committee for Standardization (CEN), 2016), the code for formworks, recommends the same value as mentioned before, but it also clarifies that this load must not be considered as an increment of the load of the materials over the formwork. The American code provisions on this matter are not as precise as the European codes, as the latter have more relevant definitions. However, the proposal made in this paper follows both recommendations.

3.1.2.2. Equipment

In the case of equipment, a power supply is commonly used in MSSs to ensure its functioning. Therefore, in order to establish the design load in this specific case, the maximum weight of this generator should be provided and the location should be studied in both stationary and launching stages. Also, during the construction, such irregular equipment as containers, moving panels, and others may be used. On the one hand, ASCE/SEI 37-14 (American Society of Civil Engineers, 2015) recommends a minimum value of 8.9 kN per each wheel of the equipment that can be distributed in the tire area. The same value is referenced by the AASHTO specifications (American Association of State Highway and Transportation Officials (AASHTO), 2017a, 2017b). On the other hand, EN 1991-1-6 (European Committee for Standardization (CEN), 2018c) specifies two types of equipment: non-permanent equipment and movable heavy machinery and equipment, depending on the size of the equipment. In the first case, it recommends a value of 0.5 kN/m^2 , which

in the case of an MSS can mean the weight of scaffolding, machinery, and containers. In the second case, it is recommended to make further research to establish the load most accurately. Nonetheless, in both cases, it is recommended to use more accurate information.

3.1.2.3. Material storage

Regarding the storage of materials, they may be present in the construction site, especially during the stationary stage (e.g., construction materials). When storage is considered, it must be controlled by setting the maximum according to the capacity of both MSS and the scaffold which supports it. On the one hand, ASCE/SEI 37-14 (American Society of Civil Engineers, 2015) does not set a value for the storage of materials; however, it specifies two types of material loads: fixed material loads (FML) and variable material loads (VML). The load is considered FML if it does not change its value during the construction process. This difference basically occurs due to the fact that the load factor is applied later in the combination of actions. On the other hand, EN-1991-1-6 (European Committee for Standardization (CEN), 2018c) recommends a minimum area load of 0.2 kN/m^2 and a point load of 100 kN. In addition, EN 12812 (European Committee for Standardization (CEN), 2008) sets the highest value between the real load and 1.5 kN/m^2 considering either a special area for the storage or all working areas. Likewise, EN 180201 (European Committee for Standardization (CEN), 2016) provides the same guidelines. Moreover, it also mentions that, if the working personnel load is considered together with the storage of materials load, the concomitant value cannot be over 1.5 kN/m^2 .

In addition, ASCE 37-14 (American Society of Civil Engineers, 2015) recommends the values for working surfaces. However, this provision only applies if the structure fits the definition given for the classes of working surfaces. The case more suitable to MSS is defined in this document as "light duty" which applies to concrete transport and placement by hose and concrete finishing with hand-tools. This load case, equal to 1.2 kN/m^2 , includes the working personnel, hand-operated equipment, and the staging of materials for light use. This is the most common use of the MSS, however, if it is not justified, each load must be taken individually.

Recommendations about the use of falseworks (Asociación Española de Ingeniería Estructural, 2005; Jacquet et al., 2009) establish values that include the working personnel, the walkways, and work areas, as well as the storage of material, and any additional equipment. This recommended value is equal to 1 kN/m^2 . Furthermore, recommendations concerning MSSs (Confederación Nacional de la Construcción, 2015) propose another value for the same purposes equal

to 1.5 kN/m^2 . It is limited by a maximum load of 20 kN for each walkway and a maximum total load for the MSS of 20 kN during the launching stage and 60 kN during the stationary stage. In both cases, the limits are only justified if the area loads are below the recommended value. Otherwise, the location of any higher load should be specified and its maximum value should be considered in the design independently.

3.1.2.4. Proposal

Summarizing the information presented in the previous paragraphs, a proposal for the working personnel, storage of materials and equipment may be the following. In design of the MSS, it is important to make a distinction between the stationary stage and the launching stage. During the stationary stage, because of the loading conditions, a working load of 1.5 kN/m^2 is recommended. This load must be applied in walkways and working areas of the MSS considering the possible eccentricities. During the launching stage, as it is not expected to have any working personnel on the MSS, a load that represents only the possible material or equipment over the walkways equal to 0.2 kN/m^2 is recommended. Furthermore, in case personnel are expected to be present in front of the MSS, it is preferable to add a point load that can represent this case better. For this case, a load of 0.5 kN can be sufficient.

Pouring fresh concrete has two effects: the lateral pressure and the vertical load. In most cases, the formwork closes symmetrical areas, hence the same lateral pressure is applied in both directions. Thereby, the MSS receives the same load in both directions, the resultant is equal to zero. This applies to the common case of bridges (e.g., box sections, T-girders). However, in design of the formwork over the MSS, the lateral pressure of the fresh concrete must be considered. Once the concrete starts hardening, this lateral pressure gradually stops acting on the formwork. The vertical load is exerted on the formwork until concrete starts hardening and becomes self-resistant to its self-weight. Unlike the lateral pressure, this is a gravitational load, thus, this load is applied over the formwork and transmitted to the launching girders with any additional loads attributable to joints and eccentricities.

In the case of the lateral pressure of concrete, ASCE/SEI 37-14 (American Society of Civil Engineers, 2015) provides reference to ACI 347-14 (ACI Committee 347, 2014), which allows calculating the value of this load. However, this last code has several limitations when the element is not vertical (e.g., box sections) and for low values of the slump of the concrete (e.g., self-consolidating concrete) which, in some cases, is not valid for the concrete mixture used in bridges. Hence, it recommends following a process of experimental tests and control during the pouring of the concrete or referring to other codes. On the

other hand, EN 1991-1-6 (European Committee for Standardization (CEN), 2018c) mentions that this load must be considered, and later DIN 18218 (Deutsches Institut für Normung, 2010) is quoted in EN 12812 (European Committee for Standardization (CEN), 2008) and EN 180201 (European Committee for Standardization (CEN), 2016) as a reference to calculate this value. In this case, the limiting condition is that it applies to a vertical formwork with a maximum angle of ± 5 sexagesimal degrees related to the vertical plane, which is not the case of some box sections. Nonetheless, it allows the use of the standard if the values are verified by experimental tests. Some recommendations concerning the use of bridge falsework and MSS (Asociación Española de Ingeniería Estructural, 2005; Confederación Nacional de la Construcción, 2015; Jacquet et al., 2009) also recommend the DIN 18218 despite the limit of the angle. Similarly, they mention that experimental procedures are needed to validate its use. Some typical values of the maximum lateral pressure based on the empirical evidence presented in these documents are between 10 kN/m^2 and 50 kN/m^2 .

In the case of the vertical load of fresh concrete, ASCE/SEI 37-14 (American Society of Civil Engineers, 2015) and ASCE/SEI 7-16 (American Society of Civil Engineers, 2017) recommend to define the load according to the geometry of the cross section and the specific weight of the fresh concrete. In this matter, despite values of specific weight of reinforced concrete are recommended, it is not considered the fresh aspect which, normally, would increase these values. It is recommended to obtain the values for materials not mentioned in these standards by referring to the appropriate bibliographic sources. AASHTO Guide Design Specifications for Bridge Temporary Works (American Association of State Highway and Transportation Officials (AASHTO), 2017b) is one of these sources, it recommends an extra 5% to the normal value of the reinforced concrete. If normal reinforced concrete is used, the value is 25.5 kN/m^3 (24.3 kN/m^3 as the specific weight of normal reinforced concrete). On the other hand, EN 1991-1-1 (European Committee for Standardization (CEN), 2019b) sets a specific weight for the concrete and adds 1 kN/m^3 if it is reinforced and 1 kN/m^3 if it is fresh concrete. Thereby, the weight of the fresh reinforced concrete would be equal to the specific weight of the concrete about to be used plus 2 kN/m^3 . In case of conventional reinforced concrete, this value is equal to 26 kN/m^3 . Additionally, EN 12812 (European Committee for Standardization (CEN), 2008) and EN 180201 (European Committee for Standardization (CEN), 2016) recommend using a value of 25 kN/m^3 as the specific weight of the fresh reinforced concrete. Correspondingly, many authors (Asociación Española de Ingeniería Estructural, 2005; Confederación Nacional de la Construcción, 2015; Jacquet et al., 2009)

also adopt this value as the specific weight of the reinforced fresh concrete with regard to their experience with MSSs.

All European codes mentioned above used for the calculation of the vertical load of fresh concrete also recommend adding an additional load to account for the placing effect of the concrete over the formwork. This load is more important in design of formwork than in design of MSS, and it is out of the scope of this paper. For the reader's convenience, any of the codes mentioned can be consulted for the value of this load.

The proposal with regard to the fresh concrete effects may be the following. As it was mentioned previously, the lateral pressure is not present in the design of the MSS as the resultant load is zero. Thereby, it must be considered only if the cross section is not symmetrical, conducting appropriate tests in order to either validate it against DIN 18218 (Deutsches Institut für Normung, 2010) or ACI 347-14 (ACI Committee 347, 2014) or to get a better approximation of this load to control it during the construction process. For the vertical load of the concrete, it is recommended to use the value of 25 kN/m^3 as specific weight of the reinforced concrete due to the several bibliographies that recommend it based on both experience and theoretical fundament. At the same time, the type of concrete about to be used should be considered. If it is not conventional concrete, the fulfilment of this recommendation must be analysed. Moreover, a design cross section that can validate its value for different cases of bridges must be studied. Normally, the concrete load considered, coming from multiplying the area of the design cross section and the specific weight of the reinforced concrete, is higher than the weight of conventional bridge deck, thus more suitable for a large number of bridges.

3.1.3. Variable loads

3.1.3.1. Thermal loads

The thermal loads are among the most important variable loads. The temperature effect on the MSS is more important when it is a structure with relevant dimensions, as it can impose additional stresses on the most loaded elements. Moreover, depending on the type of supports, it can increase the horizontal forces. An accurate representation of the degrees of freedom must be considered in order to calculate properly the forces that will appear due to thermal displacements on the structure (Rosignoli, 2013). Another important effect of temperature is observed in the interaction between the concrete deck of the bridge and the MSS. It is caused by differential horizontal displacements of the superstructure if it is of significant length that can affect the MSS. Therefore, variation of the suspension support location must be considered. This parameter

may be controlled by adding fixed supports to the bridge to decrease the value of this displacement by considering only the length between the fixed support and the MSS in the calculation. However, it must be analysed when selecting this solution or to give an extra mechanism to the MSS to withstand this action. Normally, the MSS is designed to support thermal displacements of the bridge using a non-sliding support in the front of the structure (Rosignoli, 2013). This effect can be amplified in the closing span of the bridge (Pacheco et al., 2011).

There are no specific recommendations with regard to the direct thermal effects on the MSS in either American or European code provisions. Calculation of these effects should follow the standards for thermal actions. In the USA, it is recommended to follow the calculation process laid down by the AASHTO standards (American Association of State Highway and Transportation Officials (AASHTO), 2017a). Although this standard applies to bridges, it may be also used in relation to MSSs, but the values presented in the standard are not specific enough. In the case of Europe, EN 1991-1-5 (European Committee for Standardization (CEN), 2018b) lays down the rules for the calculation of the thermal effects on structures, but the standard does not cover any bridge construction equipment (BCE). Correspondingly, the closest case is the thermal effect on bridges, possibly higher than the real effect on MSSs.

Apart from the calculation process, the standards depend strongly on the location of the bridge. An MSS may appear inappropriate if it is not designed for a specific location. In this regard, the European code of falsework and formwork suggests some values. In EN 12812 (European Committee for Standardization (CEN), 2008), it is recommended to consider thermal effects if the length of the structure span over the scaffolding is over 60 m. In this case, the effect of ± 10 K of temperature variation must be considered. EN 180201 (European Committee for Standardization (CEN), 2016) recommends the same, but if the span length is below the limit, it can be considered a limit value of thermal displacement equal to 6 mm. Some other guidelines (Asociación Española de Ingeniería Estructural, 2005; Confederación Nacional de la Construcción, 2015) adopt the recommendations provided by these two European codes. With regard to the thermal effects of the bridge, the standards for bridges mentioned above should be followed and the effect in the MSS should be checked by an appropriate method.

For the induced movements due to the thermal loads on the bridge, it is clear to follow the correspondent code provisions given by each location to check the induced movements and their effect on the MSS. In order to account for the thermals effect due to the properties of the structure, it is recommended to use the method of calculation for bridges considering its location and apply a temperature variation of ± 10 K.

3.1.3.2. Wind loads

The wind is the other climatic action that affects MSSs. The effect is realised as a lateral pressure on the structure, transversal and longitudinal, normally not simultaneously, caused by the blowing wind, and as a vertical pressure caused by the lifting effect. The wind effect cannot be limited to a specific location, as it is used for many projects. Similar to the case of any BCE (Rosignoli, 2013), special values are set for operational winds and the out-of-service wind that may affect MSSs. The operational winds are the limit winds, at which the use of the MSS is permitted for construction of the deck bridge. Different limits for each stage are commonly established. The out-of-service wind is the maximum wind that the MSS can withstand. For this last case, the configuration is in the stationary stage position where it can present additional mechanisms to help the structure resisting this wind (Rosignoli, 2013).

The principal effects of the wind load are the following. During the launching stage, an MSS can be subject to some instabilities when it reaches the maximum cantilever. In addition, in both stages, the natural frequency of the transversal bending mode varies, which can result in two different problems: those related to MSS configuration and those related to the interaction between the bridge piers and the MSS. In the first case, depending on the height of the piers and the slenderness of the MSS, it can add some dynamic response induced by possible turbulence and resonance (Meskouris et al., 2019). In the second case, depending on the same aspects, the natural frequency of the whole system tends to be lower, especially during the stationary stage after pouring the concrete, which can introduce some aeroelastic phenomena, such as galloping, vortex shedding, and flutter on the structure (Alonso, 2013; Meskouris et al., 2019; Pacheco et al., 2011; Rosignoli, 2013). In these cases, it is better to perform accurate calculations (e.g., wind-tunnel tests, step-by-step analysis).

Calculation of wind loads must be performed using the appropriate method. ASCE/SEI 37-14 (American Society of Civil Engineers, 2015) allows using a reduction factor to the basis wind speed unless the location is vulnerable to hurricanes. This reduction occurs due to the duration of the construction stage. Then, ASCE/SEI 7-16 (American Society of Civil Engineers, 2017) must be followed for the calculation of the wind pressure, but the scope of this code is limited to bridges, and it is recommended to use a more appropriate source for other structures. Hence, the AASHTO LRFD Bridge Design Specifications must be followed. On the other hand, in the case of Europe, there is a code EN 1991-1-4 (European Committee for Standardization (CEN), 2018a) which addresses the wind actions. In addition, EN 1991-1-6 (European

Committee for Standardization (CEN), 2018c) presents a lower return period for climatic actions, which depends on the duration of the construction stage. Although the main equation in both codes is similar, the formulas that consider the return period (André et al., 2012; André et al., 2013), the pressure exposure coefficient, and the drag coefficient and force coefficient are different. Particularly, the reduction factor, because of the return period, can have a very sensitive difference for low values of return period and it starts being more stable for a return period higher than 50 years. Moreover, these differences are what make them possibly insufficient for construction stages equal or over a year when this has many incidents during this period. For this reason, it is strongly recommended to conduct specific studies of wind loads, especially for long spans (Pacheco et al., 2015).

In both codes, no specific values are set for design of MSSs, such as zone, height, and other aspects. In any case, the limitations for the wind loads in terms of the operational wind and the out-of-service wind are set. The closest approximations are found in some European codes, where some values for the service and maximum wind are recommended. For the maximum wind, a value of 50 years as a return period is suggested, but it can be lower depending on the duration of construction which must be justified by EN 1991-1-6 (European Committee for Standardization (CEN), 2018c). For the service wind, the value of 0.2 kN/m^2 is recommended (European Committee for Standardization (CEN), 2005, 2008). Cranes are the closest case to MSS, which is described in EN 1991-3 (European Committee for Standardization (CEN), 2012), the maximum wind for crane operations is set at 20 m/s.

Because of the lack of information with regard to wind speed limits for MSSs, some recommendations about their use (Asociación Española de Ingeniería Estructural, 2005; Confederación Nacional de la Construcción, 2015; Jacquet et al., 2009; Pacheco et al., 2011; Rosignoli, 2013) propose the following. An average value between 10 m/s and 12 m/s and a peak value of 16–18 m/s for the basis wind speed are recommended for the launching stage operational wind. For the out-of-service wind, the recommended values range between 38.9 m/s and 47.2 m/s or a return period of 10 years with the maximum basis wind of the location chosen.

3.1.3.3. Other variable loads

Another possibly variable load is the snow, but this effect is negligible with respect to the other variable loads.

Finally, the earthquake effect, normally, is not considered due to the low probability of occurrence. However, if it is located in an area

with considerable seismic activity, it must be followed the respective standards: the ASCE/SEI 7-16 or AASHTO Standards using the correspondent reduction factor (American Association of State Highway and Transportation Officials (AASHTO), 2017a; American Society of Civil Engineers, 2015, 2017), and EN 1998-1 and EN 1998-2 (European Committee for Standardization (CEN), 2018d, 2018e). For the return period, due to several recommendations on MSSs and bridge falseworks, it should be considered at least four or five times the time the concrete is over the formwork until it obtains its resistance (Asociación Española de Ingeniería Estructural, 2005; Confederación Nacional de la Construcción, 2015; Jacquet et al., 2009).

3.1.3.4. Proposal

Considering the data presented in the previous paragraphs, the following proposal is made. First, it is necessary to differentiate the types of wind and set values for the operational winds and out-of-service wind. Second, the reference values for the operational wind during the launching stage should not be higher than 16 m/s and the out-of-service wind should be calculated setting the design basis speed and a return period of 10 years, if it is justified by duration of construction. The remaining parameters for the calculation of wind loads should be chosen by the MSS designer. Third, if the out-of-service wind or maximum wind can condition the behaviour of the MSS, alternative structures must be designed that can help control behaviour of the MSS, such as anchorages to the deck bridge. Finally, the method of calculation must follow either the AASHTO Standards (American Association of State Highway and Transportation Officials (AASHTO), 2017b, 2017a) or EN 1991-1-4 (European Committee for Standardization (CEN), 2018a), but two specific studies should be conducted in order to analyse wind variation in the location of a bridge depending on duration of construction and the possible dynamic effects in accordance with the appropriate standards and/or experimental tests.

3.1.4. Accidental loads

The accidental loads are essentially the use limitations for the MSS that may happen during its utilisation and the malfunction of some structural or mechanical component (Rosignoli, 2013). In the first case, this depends strongly on the type of MSS; the limitations normally apply to the launching stage, such as movement speed, possible higher admissible gap between one of the girders related to the other, and others (Rosignoli, 2013). In the second case, accidental loads may be caused by collisions with buffers and failure of some joint (Pacheco et al., 2011; Rosignoli, 2013). Hence, calculation of these loads depends on

the type of MSS and the main structural typology. Recommendations regarding the accidental loads are aimed at control of the limitations of MSSs during construction, control of the nominal speed during launching to avoid collision with the buffers, and provision of structural redundancy to counter the possible failure of joints either due to wrong assembly or inefficient maintenance.

3.1.5. Other loads

In design of supports, not only the vertical loads, but also the minimum horizontal load should be considered, taking into account the slope and transversal inclination of the deck, and the roughness of the supports. ASCE/SEI 37-14 (American Society of Civil Engineers, 2015) recommends a minimum horizontal load equal to the maximum value between 2% of all vertical loads and 0.22 kN/m per worker. However, if the real value is higher, then the higher value must be chosen. On the other hand, EN 1991-1-6 (European Committee for Standardization (CEN), 2018c) recommends a value of 10% of the vertical loads for launched bridges, which is the closest case to the launching stage of MSSs. At the same time, EN 12812 and EN 180201 (European Committee for Standardization (CEN), 2008, 2016) recommend a minimum of 1% of the vertical loads. The difference between these last two European codes is that whilst a launched bridge normally has a higher horizontal reaction than an MSS, bridge falsework and formwork normally do not account for this launching aspect. For this reason, the manual of MSSs (Confederación Nacional de la Construcción, 2015) proposes a minimum of 5% of all vertical loads. Therefore, the proposed minimum horizontal load is a minimum of 5% of the vertical loads. Nevertheless, the real values must be considered, since the roughness of supports can be substantially higher (Members of IABSE WG 6, 2018).

As a resume of the design aspects discussed in the previous sections, a summary of the code provisions of the proposal is provided in Table 1.

**Table 1. Summary of design loads by code provisions, recommendations,
and proposal**

Load type	USA codes	European codes	Recommendations	Proposal
Permanent Loads				
Self-weight	ASCE/ SEI 7-16 / AASHTO Standards	EN 1991-1-1	ASCE/SEI 7-16 / EN 1991-1-1	ASCE/SEI 7-16 / EN 1991-1-1
Dead load	ASCE/ SEI 7-16 / AASHTO Standards	EN 1991-1-1	ASCE/SEI 7-16 / EN 1991-1-1	ASCE/SEI 7-16 / EN 1991-1-1
Construction Loads				
Working personnel	ASCE/ SEI 37-14: 1.11 kN per worker	EN 1991-1-6: 1 kN/m ² EN 12812/12811/180201: 0.75 kN/m ²	ACHE, <i>fib</i> *: 1.0 kN/m ² CNC*: 1.5 kN/m ²	During stationary stage*: 1.5 kN/m ² During launching stage*: 0.2 kN/ m ² + 0.5 kN per worker
Equipment	ASCE/SEI 37-14: 8.9 kN per wheel	EN 1991-1-6: 0.5 kN/m ²		
Storage of materials	ASCE/SEI 37-14	EN 1991-1-6: 0.2 kN/m ² + 100 kN		
Fresh concrete				
Vertical pressure	AASHTO: 1.05% specific weight of concrete	EN 1991-1-1: 26 kN/m ³ EN 12812/180201: 25 kN/m ³	ACHE, CNC, <i>fib</i> : 25 kN/m ³	25 kN/m ³
Lateral pressure	ACI 347-14	DIN 18218-10	DIN 18218-10	ACI 347-14 / DIN 18218

Load type	USA codes	European codes	Recommendations	Proposal
Variable Loads				
Thermal	-	EN 12812/180201: ±10 K for span lengths over 60 m. If not, a maximum displacement of 6 mm	ACHE, CNC: ±10 K for span lengths over 60 m. If not, a maximum displacement of 6 mm	±10 K for span lengths over 60 m. If not, a maximum displacement of 6 mm
Wind				
Operational	-	EN 12812: 0.2 kN/m ² EN 1991-3: 20 m/s as basis wind speed	ACHE, CNC, <i>fib</i> , Pacheco: 10–12 m/s for average basis wind speed and 16–18 m/s for average basis wind speed during the launching stage	Launching stage: Basis wind speed ≤16m/s. Consider possibly dynamic effects
Maximum	-	EN 12812: Return period of 50 years	CNC: Return period of 10 years	Return period of 10 years
Snow	ASCE/SEI 37-14	EN 1991-1-3	EN 1991-1-3	ASCE/SEI 37-14 / EN 1991-1-3
Earthquake	-	-	Return period of minimum 4 times, duration of concrete hardening	Return period of minimum 4 times, duration of concrete hardening
Accidental Loads	-	-	Possible failure of an element or usage of the MSS out of its limits	Possible failure of an element or usage of the MSS out of its limits
Others Loads				
Horizontal load	ASCE/SEI 37-14: 2% of the vertical load or 0.22 kN per worker	EN 1991-1-6: 10% of the vertical load. EN 12812/180201: 1% of the vertical load	CNC: 5% of the vertical load	5% of the vertical load

* total load considering working personnel and storage of materials. The power generator load value must be provided by the supplier;

** total load considering the working personnel and storage of materials.

3.2. Safety factors

Safety factors are divided into two categories: safety factors for materials and safety factors for loads. Furthermore, it is common to establish concomitant factors, when more than one variable load is used in the load combinations. However, these are defined for permanent structures as they operate in different contexts during their life cycle. Accordingly, in case of MSSs it is better to disregard these concomitant factors as they do not share the load combinations of a bridge, hence, the load combinations must be performed comprehensively (Rosignoli, 2007, 2013).

With regard to the safety factors of materials, the specifications for steel as applied in bridge construction should be followed as a minimum requirement: the AASHTO LRFD Bridge Design Specifications (American Association of State Highway and Transportation Officials (AASHTO), 2017a) and the AISC design standards (AISC (American Institute of Steel Construction), 2016a, 2016b) in the US, and EN 1993-1 and EN 1993-2 (European Committee for Standardization (CEN), 2013a, 2013b) in Europe.

Regarding the safety factors of loads, the general rules for structures must be followed. Hence, the corresponding factors should be the ones for Permanent Loads, Construction Loads, Variable Loads, and Accidental Loads. There are two exceptions though. The first, the working personnel, must be considered as the live load, or variable load, and the second, the concrete load, must be considered as the permanent load (American Association of State Highway and Transportation Officials (AASHTO), 2017a; American Society of Civil Engineers, 2015; Confederación Nacional de la Construcción, 2015; European Committee for Standardization (CEN), 2019a).

3.3. Load combinations

Specifications on the load combinations for bridges are not applicable to MSSs, the ones for permanent structures are not applicable either. Hence, following the definitions of loads mentioned above, it is recommended to follow the load combinations from Eq. (1) to (4), as suggested in different recommendations (Asociación Española de Ingeniería Estructural, 2005; Confederación Nacional de la Construcción, 2015; Däbritz, 2011; Jacquet et al., 2009; Pacheco et al., 2011; Rosignoli, 2007, 2013). During the stationary stage, two limit situations must be differentiated: pouring of the concrete and the maximum wind condition. The main difference is that the concrete load and construction loads are present during the pouring of the concrete, but they do not

necessarily exist during the maximum wind condition. Therefore, the following load combinations (*LC*) are recommended as a minimum.

$$LC_1 : \text{PermanentLoads} + \text{ConstructionLoads} + \text{VariableLoads}, \quad (1)$$

$$LC_2 : \text{PermanentLoads} + \text{ConstructionLoads}, \quad (2)$$

$$LC_3 : \text{PermanentLoads}, \quad (3)$$

$$LC_4 : \text{PermanentLoads} + \text{VariableLoads}. \quad (4)$$

Eq. (1) is valid in the stationary stage during the pouring of the concrete, Eq. (2) and Eq. (3) account for the presence of the operational wind, Eq. (3) is valid during the maximum wind condition, and Eq. (4) – at the maximum wind. During the launching stage, considering the possible differences in the wind load and variation in the construction loads mentioned before, Eqs. (1) to (3) are valid.

For the ultimate limit states, all combinations mentioned before are valid, but they must be subject to the safety factor for loads according to the code provision in use. Thus, there may be more load combinations depending on the varying maximum and minimum safety factors. In these states, the following ultimate limit states must be assessed: loss of static equilibrium, internal failure or excessive deformation, and fatigue (Coelho et al., 2017; Pacheco et al., 2011; Rosignoli, 2007). Different limits for each state are given in the code design for steel of each country.

For the service limit states (SLS), all combinations mentioned before are valid. However, as there are no safety factors set for the service limit states, load combinations must be followed in the way they are presented in the codes, considering possible variations of wind direction to assess the worst combinations. Thus, normally Eq. (1) might be the most demanding for the structure as there are present all the possible loads. Nevertheless, all equations must be analysed. Deformations are the limitation in SLS. On the one hand, for this matter, the maximum deflection for the centre span during the stationary stage is normally recommended at a value of $L/400$, being L the span length of the bridge (Confederación Nacional de la Construcción, 2015). The same value is recommended by EN 180201 (European Committee for Standardization (CEN), 2016) and has been proved effective for poured span lengths up to 70 m (Gonçalves Bezerra, 2008; Vasques de Carvalho, 2008). On the other hand, if the OPS is used in the MSS and the bridge span length is higher, the deflection control is more exhaustive and the value of $L/1000$ is recommended, being L the span length of the bridge (Pacheco et al., 2011). These two values are recommended based on experience and

good results of some MSSs designers and projects (Pacheco et al., 2020). The deflection for the cantilevers of the MSS is conditioned by how the structure reaches the next pier and its limits, which are related to the nose of the MSS.

3.4. Structural analysis and design

Structural analysis depends on the level of analysis of the MSS (i.e., global or local analysis), the structural typologies of the MSS, and the level of accuracy of each type of analysis that is needed (Members of IABSE WG 6, 2018). Therefore, depending on the MSS, the such types of analysis as strains and stresses in sections, second-order analysis due to imperfections, buckling analysis of plate panels and single elements, fatigue analysis, dynamic analysis and step-by-step analysis due to wind loads, bridge-MSS interaction, joints analysis, and deflection results may be employed (Coelho et al., 2017; Rosignoli, 2007, 2013).

In any case, the Finite Element Method (FEM) is highly recommended, but the type of elements (e.g., beam elements, shell elements) depends on which results are needed. To obtain general results regarding stresses and strains, a single element for cross section can be a good approximation. However, in the case of truss elements, this analysis does not consider the real inertia and cannot represent an accurate condition of supports during launching. Hence, a model should consider the 3D aspects of the truss and box sections, if any. An example of this is represented in Figure 1. Therefore, this model should correctly represent not only the structural components but also the type of joints and supports. Then, the rest of the structure (formwork supporting structure and others) can be neglected in the model, but their effects on the main launching girder must be considered.

Due to the possible residual or secondary effects on trusses (Argüelles Álvarez et al., 2005; Boyd, 1954; Korol et al., 1986), secondary effects must be considered as the trusses of MSSs fulfil the conditions to consider them. Thus, the model should include their components, and beam elements and the joints should be represented in two cases: with an ideal joint and with the real joint considering possible eccentricities. In any case, these aspects must be assessed depending on the geometry of the structure.

Accounting for the aspects mentioned before, the model should be accurate enough to perform most of the analyses mentioned. The buckling analysis, the fatigue analysis, the interaction bridge-MSS, and the joints analysis are excluded. For the panels on beam cross sections or elements of trusses prone to buckling failure, the fatigue analysis, and the joint analysis, it should be considered an analysis

with shell elements. This because of the higher level of accuracy needed to reproduce those effects on the panels of a box section or of a truss element (Coelho et al., 2017; Mørch Larsen, 2011; Rosignoli, 2007). The use of these elements and the judgment of the results should be assessed by simplifications and recommendations given by steel standards and, also, these analyses should be performed by an experienced designer on these aspects. Furthermore, the analysis of the complete structure or partial structure with shell elements must be considered to calibrate the results obtained before. For the last aspect, the interaction between the bridge and the MSS due to induced temperature loads might need a partial representation of the bridge. Thus, due to the complexity of the elements involved, some simplifications can be considered, but they must not compromise the safety of the structure. This study should be specifically performed in the case of long span bridges.

The design should be implemented thinking on the structural redundancy of the MSS considering the possible accidents. The joints that are reused because of the module partition of the whole structure are the critical elements of the structure. Due to the assembling configuration, there are eccentricities that should be evaluated and limited depending on the design. Finally, all mechanical, electric and hydraulic parts should be designed and chosen according to the behaviour of the MSS. They should not condition the design. Therefore, the manual regulating the design and use of each of these elements and the MSS shall describe all decisions, operational limits, and design aspects that the MSS designer should consider.

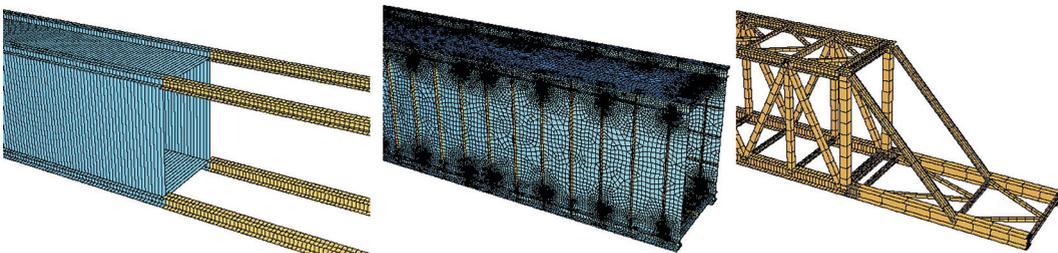


Figure 1. From left to right: Linear beam elements for the whole MSS, shell elements for the MSS box section, 3D beam elements for the MSS truss

Conclusions

This paper has analysed different aspects to be considered in design of MSSs. A large number of European and American codes has been analysed and critically reviewed from a structural perspective. Although there are plenty of available code provisions, there is a noticeable lack of information concerning structural MSS design. Therefore, several recommendations were collected to shed light on this subject. As a result, a comprehensive basis and a source of information on the design of MSS has been developed, which may guarantee a considerable level of safety in MSS design, backed by actual and official code provisions. In fact, the European and American codes share certain guidelines that enable their use for applications out of their scope. This allows their utilisation for MSSs and the definition of a reasonable design procedure.

The research initiated in this paper may be followed by recommendations on the missing aspects concerning the design and analysis of MSS, as well as recommendations on the use of MSSs in the bridge construction. In addition, other relevant aspects, such as the mechanical, electric, or hydraulic parts of an MSS (which are out of the scope of this paper) should be considered in an extended version of this design basis.

It may be noted that this paper represents a unique source of information on the structural design of MSSs and it may be used as a basis for development of respective code provision valid in Europe and the USA.

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Design basis
of Movable
Scaffolding Systems
following American
and European code
provisions and
recommendations