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Assessment of a movable scaffolding system under temporary use conditions

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ABSTRACT

Current structural standards like the Eurocodes do not provide a coherent framework for design or assessment of structures under temporary use conditions. The reliability requirements for temporary systems put forward in the present study seek to ensure the same acceptable risk levels per unit of time as for permanent structures in the current best practice. The results obtained show that the target reliability index for structural members rises significantly with declining risk exposure times. Conversely, the design values for variable actions may be lowered in keeping with the duration of construction, as illustrated in a case study: analysis of a movable scaffolding system for bridge erection.

KEYWORDS: Bridge construction, Temporary structures, Risk, Reliability, Acceptance criteria.

1. Introduction

Standardized ancillary elements, designed to be reused after adaptation to the specific characteristics of each new building or bridge structure, are increasingly sophisticated. Their employment, in general, and the interaction with the structural system under construction in particular, entail considerable risks that are often poorly understood. Relatively large frequencies of failure are observed for temporary structures, especially for ancillary systems used in construction procedures [1]. Forensic investigations of construction accidents reported in the literature [2 – 11] conclude that the causes of failure can in many cases be traced back to some manner of gross human error. Improvement of this situation can be achieved by adopting organizational measures such as an unequivocal definition of the tasks, activities, skills and responsibilities of the actors involved in construction planning and building. Moreover, effective quality assurance is a crucial tool for the early detection of possible gross errors and hence for improving the strategies presently in place to reduce construction-related risks [12].

One inference of the foregoing is that many of the temporary activity-related problems in everyday construction are rather elementary, that is, often associated with influences not covered by the partial factors defined in structural design codes. However, some risk acceptance criteria are always needed in structural engineering. A consistent approach for temporary structures is currently lacking, being one of the consequences that the associated reliability levels exhibit large variation and are often smaller than those corresponding to permanent structures [13]. A need for a coherent framework and guidance for design of temporary construction equipment is identified including the choice of appropriate target reliability levels [14]. Regarding this challenge, some basic principles were recently formulated [15]. It was suggested that the fundamental basis for choosing the levels of safety for temporary structures or structures under temporary use shall not be different from those applied to permanent structures and should be fixed taking account of both, possible failure consequences and relative costs for risk-reduction measures. Moreover, in view of the important consequences the failure of structures under temporary use might entail, it is felt that there is no meaningful reason to choose a priori lower safety levels for such structures just because of their temporary use conditions [15].

Taking into account these considerations, target reliability levels for structural members under temporary use conditions were recently suggested [16]. The developments are based on the results of a prior study [17] where structural safety requirements were inferred from implicitly acceptable life safety risks associated with structures designed in compliance with present best structural engineering practice. After a brief presentation of these developments in section 2, the present paper illustrates their practical application by means of a case study: the analysis of a movable scaffolding system (MSS) used for erection of the access viaducts of the Pumarejo bridge in Barranquilla, Colombia. A short description of the bridge and the MSS is given in sections 3 and 4, respectively. Subsequently, section 5 addresses aspects concerning analysis and verification of the temporary system's structural safety. Section 6 includes some final remarks.

2. Target reliabilites for temporary structures

2.1 Current situation

There is currently no general agreement in place among responsible authorities, code writing committees and practitioners about which reliability levels, e.g. target reliabilities or partial factors, as well as other risk reduction-measures, e.g. quality assurance levels, should be applied to transient situations and temporary structures [15, 18]. Considering that, in comparison with permanent structures, exposure to extreme events is less likely, lower safety standards are often suggested for the design and assembly of temporary structures, e.g. [19], regardless of the specific case and design situations under consideration.

However, one of the important aspects in relation with temporary structures is the existence of many different objectives and design situations [15]. Some structures are used only once during a short period of time, while others may be reused several times, building up a substantial accumulated service life. In the latter case it must further be distinguished between, respectively, reuse as an exact copy at another location or reuse on an individual basis. The latter situation is applicable to standardized ancillary elements, reused for the construction of different permanent structures. In this frequent case, the continuously changing temporary construction stages might imply higher uncertainties associated with actions, resistances and the models used for analysis than those for the permanent structures [1, 12, 13]. This in turn would mean that higher target reliabilities and partial factors should be adopted for the design of the temporary structures, in spite of their aforementioned comparatively lower likelihood of exposure to extreme events. Moreover, higher safety requirements seem to be defendable in the light of relatively low costs of safety measures compared to the potentially large consequences in case of failure [20], including loss of human life. Life safety must always be addressed when establishing reliability requirements, and might become especially relevant for short use periods of a structure [14, 18, 21].

2.2 Proposal

A recent study addresses the challenging issue of establishing acceptable risks and associated target reliability levels, taking account of temporary use conditions of structures [16]. The developments are based on the condition to maintain the same acceptable risk levels per time-unit as for permanently occupied building structures that are strictly compliant with the safety requirements set out in the current Eurocodes [22], and which, further to international standard about general principles on reliability for structures [23], constitute present best structural engineering practice associated with risk acceptance criteria for human safety. Using a life safety risk metric, which relates risk exposure due to different activities and applied technologies, it is shown that the target reliability index for structural members significantly increases when short risk-exposure times are considered. Depending on the expected failure consequences and the share μ of the reference period T_{ref} during which persons are temporarily exposed to risk, the required risk-based reliability levels may exceed the general target values demanded by current codes and standards. The derived criteria in terms of the target reliability indices $\beta_{t,LR,T}$, associated with a reference period of T_{ref} = 1 year, are plotted against the area affected by collapse of the structural member in question, A_{col}, assuming different values for parameter μ (Figure 1). The lowest curve corresponds to permanent risk exposure for system users (μ = 1). These criteria may be applied within the framework of an explicit reliability analysis or constitute the basis for consistent calibration of the partial factor models used in everyday practice. Regardless of the approach adopted, they should be consistently used in connection with a time-dependent adjustment of the probabilistic models for the relevant variable actions (section 2.3).

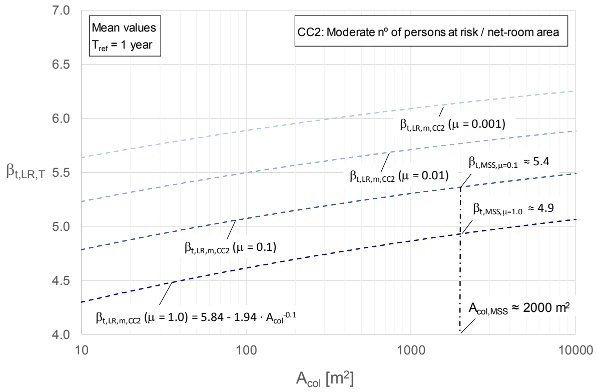

Figure 1. Target reliability index ($\beta_{t,LR,T}$) for members in temporary structures, belonging to consequence category CC2 [22], versus the area affected by member collapse (A_{col}) based on the mean value of implicitly acceptable risks.

2.3 Influence of duration of temporary use on variable actions

The foregoing developments show that target reliability indices for members in temporary structures may be significantly higher than the values suggested for permanent structures. Higher target reliabilities, in turn, will entail higher partial factors for the materials and the loads. However, when verifying structural reliability, the representative values for the relevant variable actions should also be adjusted to the duration of temporary use [12, 18, 21]. Again, that entails drawing a distinction between structures used only once during a short period and those reused several times at the same or at different locations [15]. Depending on these circumstances, the return periods for variable loads can be defined and the associated exceedance probability be established, as shown by different authors, e.g. [20, 24]. Guidance for the establishment of return periods in function of the temporary use duration of construction procedures can be found in the Eurocode [25].

3. Pumarejo bridge

The Pumarejo Bridge over the Magdalena River constitutes the principal element of the currently undergoing construction works to improve the access conditions to the city of Barranquilla (Colombia). The general configuration of the bridge is influenced by navigation requirements for large vessels on the river (clearance gauge 45 m). A cable-stayed solution was chosen spanning 380 meters between the two approximately 135 meter-high principle bridge pylons (Figure 2). The cable-stayed bridge, with a total length of 800 m, is connected at both ends to access viaducts, continuous over 10 and 12 spans, respectively, with a typical span length of 70 m. The total bridge length is 2173 m.

Bridge pylons and piers are constituted by rein-forced concrete. The bridge superstructure consists of a continuous, prestressed concrete box girder of constant depth (3.65 m) and deck slabs with a maximum width of 38.1 m in the cable-stayed section, gradually reducing to 35.1 m towards the access sections.

Figure 2. Computer graphics of the Pumarejo bridge crossing the Magdalena River in Barranquilla (www.sacyr.com).

4. Construction of the access viaducts

For the span by span in situ construction of the superstructure of the two access viaducts, a movable scaffolding system (MSS) is being employed. The MSS is provided by the company BERD, S.A., author of the corresponding MSS design project [26]. Third party checking of this project from the structural point of view was carried out by CESMA Ingenieros S.L. For this purpose, the aforementioned reliability requirements have been applied [27].

The main girder of the MSS, shown in Figure 3, consists of a spatial truss with an upstanding arch and tensile system, both appropriate for load transfer during the different construction stages. The front and the rear part of the girder are equipped with launching noses. During the successive concrete casting and launching stages, the main girder rests on different auxiliary support frames and props, situated on top of the previously erected bridge decks or on top of the bridge piers. Figure 3 shows the position of the MSS during the casting stage, supported at two sections, with the rear support frame located on top of the previously erected bridge deck at a distance of 10 m from the rear bridge pier of the span to be casted, and the front support frame situated on top of the front bridge pier of this span.

For the casting operations, a truss-type substructure is suspended from the main girder by means of wings and ties to support the formwork panels that contain the fresh concrete of the bridge superstructure (Figure 4). Concrete casting is carried out in two stages. At first, the U-section of the box girder is casted, followed by pouring of the top slab in a second stage.

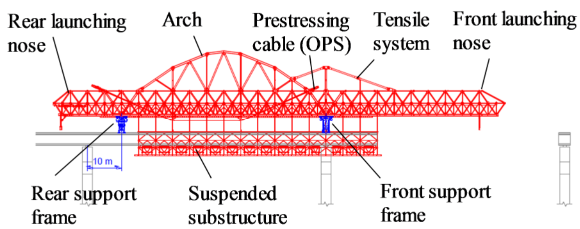

Figure 3. Elevation of the MSS main girder including suspended substructure for support of the formwork panels [28].

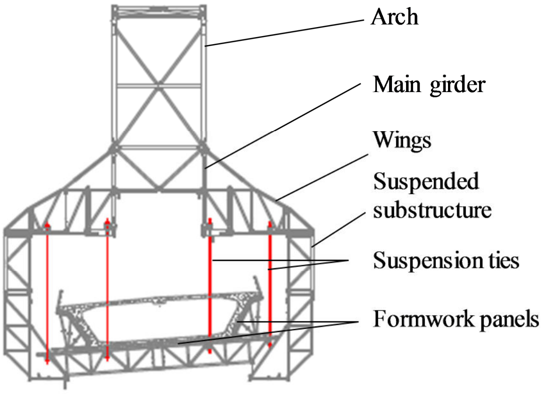

Figure 4. Cross-section of the MSS main girder including suspended substructure for support of the formwork [28].

The MSS is provided with an organic prestressing system (OPS), able to self-adjust the forces in the pre-stressing cables [29]. The OPS system is especially effective in structures where ratios between live and dead loads are high, such as in MSS, where it provides an efficient tool for deflection control, in addition to an increase in the load carrying capacity [30]. Figure 5 shows the principal components of the OPS integrated into the MSS employed for erection of the access viaducts of the Pumarejo bridge. A trilinear configuration of the un-bonded prestressing cables is achieved by means of deviation shores. The active and passive anchorage devices as wells as the OPS actuators, are situated at both ends of the cables, above the top chords of the main girder.

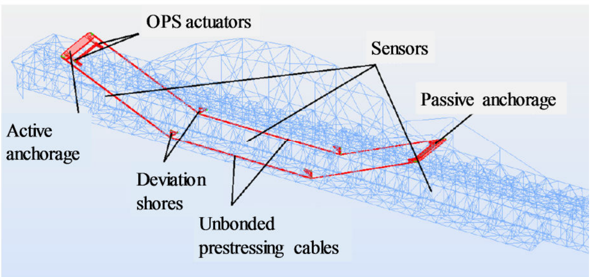

Figure 5. Main components of the OPS [28].

5. Analysis

5.1 Procedure

The present section summarizes the tasks related to the independent review of the structural design project [27]. With bridge construction stages and ancillaries defined (section 4), structural safety of the system as a whole was verified. That entailed performing the following tasks in each construction stage:

- identification of all possible hazards to which the system may be exposed;
- definition of hazard scenarios;
- establishment of reliability requirements and models for significant variables;
- establishment of a model for structural analysis;
- structural analysis for relevant hazard scenarios;
- verification of structural safety.

Some important aspects concerning the definition of the relevant hazards and hazard scenarios to the MSS are summarized in section 5.2. The establishment of reliability requirements is subject of section 5.3, followed by specific considerations on time-dependent models for the variable actions in section 5.4. Structural analysis and subsequent safety verification are not subject of the present publication.

5.2 Hazard scenarios

Evaluating the reliability of a structure calls firstly for identifying all the possible hazards to which the structure might be exposed during its envisaged use period. This step is of crucial importance, since any unidentified relevant hazard necessarily introduces a bias in the decisions adopted during the subsequent evaluation, as a result of which misleading conclusions may be drawn. Moreover, several hazards may concur in space and time, giving rise to what is known as a hazard scenario [31]. Such situations normally generate higher risks than any individual hazard separately. Based on the classification of the potential hazards by their relevance to structural safety, each scenario is characterised by a combination of one leading and accompanying actions and influences.

The definition of the potential hazard scenarios, relevant to the design of the MSS used for erection of the access viaducts of the Pumarejo bridge, should account for all possible deviations from the expected values concerning the actions or influences, their effects on the structure and its resistance, specified below:

- MSS self-weight and permanent loads due to the formwork panels, working platforms, bridge crane and other equipment integrated into the MSS.
- Construction loads, including those stemming from the use of the bridge crane.
- Forces required to induce longitudinal and transverse movement during launching of the MSS.
- Fresh concrete, which induces significant pressure on the formwork panels. In combination with the longitudinal and cross slope of the bridge, this pressure might entail considerable internal forces in the members of the formwork-supporting substructure (Figure 4). This frequently neglected or underestimated hazard in the design of temporary structures [32] calls for appropriate resistance and stability mechanisms in the MSS constitutive members.
- Prestressing forces applied by the OPS (Figure 5).
- Climatic and seismic actions (the bridge is located in a region where high wind speeds are registered and seismic activity is likely), for which the corresponding characteristic values have to be deter-mined depending on the temporary use conditions of the MSS (see sections 2.3 and 5.4).
- Differential settlements of the bridge pier foundations.
- Other imposed deformations, for instance due to imperfections during assembly of the MSS or its support structures.
- Initial imperfections and residual stresses in the MSS components due to the fabrication process of the steel structure.
- Material characteristics.
- Strength decay mechanisms associated with variable load cycles, accentuated by dynamic effects introduced during successive launching and casting stages of the MSS.
- Insufficient lateral support causing overall instability of the MSS main girder.

Measures adopted to mitigate risks are to be considered when defining relevant hazard scenarios, including the following:

- Monitoring of the induced prestressing forces by the OPS system (Figure 5).
- Implementation of an efficient quality assurance system for prevention of human errors during the different operations, e.g. to avoid the use of the bridge crane in an unforeseen position or with an excessive load.
- Installation of alarm systems, for instance, for the case of unexpected deformations during the casting stages.
- Provision of automatic braking systems to counteract unforeseen movements during the MSS launching operations.

5.3 Reliability requirements

Assuming that the possible failure of one key member, for which the safety requirements are to be established, would lead to a complete collapse of the movable scaffolding system (MSS), the affected area can very roughly be estimated to $A_{col} \approx 2000$ m^2. For the establishment of share μ of the reference period T_{ref} the MSS is effectively used (section 2.2), the information available in the design documents [26] is applied. According to this information, the sum of the periods corresponding to the launching cycles of the MSS is about 20 days, which is less than 5% of the total construction time (Table 1). Similarly, concrete casting also requires less than 5% of construction time, as well for the first as the second casting stages (section 4). Consequently, the time period during which the MSS is in a fixed position (time for placing of reinforcement, etc.), corresponds to approximately 85% (≈ 365 days) of the total construction time. For sake of simplicity, and since the aforementioned figures are estimated values that may change depending on the site-specific conditions, the rounded values given in Table 1 were assumed for parameter μ corresponding to the different construction stages.

Table 1. Estimated duration, parameter μ and annual target reliability $\beta_{t,T}$ for different construction stages.

Construction stage	Duration [days]	μ -	$\beta_{t,T}$ -
MSS launching	20	0.1	5.4
First casting stage (U section)	25	0.1	5.4
Second casting stage (top slab)	20	0.1	5.4
MSS in fixed position	≈365	1.0	4.9

Although originally developed for building structures, as the occupancy rate roughly is of the same order of magnitude, the requirements given in Figure 1 are applied for establishing target reliability. Intercepting, for example, the curve for μ = 1.0 at A_{col} ≈ 2000 m^2 yields a required reliability index of $\beta_{t,T}$ ≈ 4.9 for design of the members of the MSS in a fixed position (Table 1). Similarly, the target reliabilities are deduced for design of MSS members in the launching and the concrete casting stages, all characterized by μ = 0.1 (Table 1). Intercepting, the corresponding curve in Figure 1 at A_{col} ≈ 2000 m^2 yields a required reliability index of $\beta_{t,T}$ ≈ 5.4 (T_{ref} = 1 year).

It should be noted that the proposed reliability requirements for the MSS design considerably exceed the current Eurocode requirement for CC2 structures and a reference period of T_{ref} = 1 year, $\beta_{t,EN1990}$ = 4.7 [22]. For a verification of structural safety according to the semi-probabilistic design format, that means that higher partial factors than those implemented in this code for reliability class RC2 structures (related to consequence class CC2) are expected. Taking account of appropriate statistical distributions (including their associated parameters) for the different variables, this reliability differentiation may be achieved by introducing so-called adjustment factors (ω_γ). These factors are defined as the ratios between the design values of the corresponding variable, obtained by factoring in the deduced target reliability index $\beta_{t,T}$ and the Eurocode value $\beta_{t,EN1990}$, respectively, considering a reference period of one year. Table 2 includes the ω_γ to be factored to the Eurocode partial factors for the resistance of steel structures [33], $\omega_{\gamma M}$, permanent and variable actions [22], $\omega_{\gamma G}$ and $\omega_{\gamma Q}$, respectively, distinguishing between the different construction stages. It can be observed that the partial factors for variable loads experience the highest increase (15% in the launching and casting stages, and 7.5% in the fixed position stage). The increase corresponding to the permanent loads and the resistance oscillates between 5 and 7.5%.

Table 2. Adjustment factors ω_γ.

Construction stage	$\omega_{\gamma M}$	$\omega_{\gamma G}$	$\omega_{\gamma Q}$
MSS launching	1.075	1.075	1.150
First casting stage (U section)	1.075	1.075	1.150
Second casting stage (top slab)	1.075	1.075	1.150
MSS in fixed position	1.050	1.050	1.075

5.4 Time dependent models for variable actions

5.4.1 General

As stated before in section 2.3, when verifying structural safety under temporary use, the representative values for variable actions should be adjusted due to reduced exposure time. In the present case study, this is particularly relevant for wind- and seismic actions. For these action ns appropriate return periods have to be fixed as a function of the estimated duration of the different construction stages under use of the MSS.

Due to lack of information, no duration dependent models are established for other climatic actions. Thermal effects, for example, are taken into account by applying vertical and horizontal gradients inferred from data available in the literature.

5.4.2 Wind actions

According to the indications in the design project of the MSS [26], a maximum value of 40 km/h (≈ 11 m/s) is assumed for the wind velocity during the launching stages of the MSS. Meteorological previsions for three days are considered to be sufficiently precise in order to assure that no launching operation (with an estimated duration of approximately 12 hours) will be undertaken if expected wind velocities exceed this value.

The total durations of the casting stages and the fixed position stage of the MSS, estimated from information provided in the design project [26], are again listed in Table 3. As a function of these durations, return periods T_R for wind actions of respectively 5 and 10 years are established, following the recommendations in the Eurocode for actions during execution [25]. Based on these return periods and taking into account the results from a specific study on wind velocities measured at different locations, representative for the Pumarejo site [34], the basic wind velocities v_b [35] to be taken into account in the design of the MSS are determined assuming a Gumbel distribution. Table 3 summarizes the obtained results.

Table 3. Duration of construction stages and associated return periods (T_R) and basic velocities (v_b) for wind actions.

Construction stage	Dur. [days]	T_R [years]	v_b [m/s]
MSS launching	20	-	11.0
First casting stage (U section)	25	5	34.5
Second casting stage (top slab)	20	5	34.5
MSS in fixed position	≈365	10	44.5

5.4.3 Seismic actions

In a specific study on the seismic hazards affecting the zone where the bridge is located [36], a ground acceleration response spectrum depending on the vibration period of the structure is defined. Since this spectrum refers to the design of the bridge in its final state, it has been established for a return period of 1000 years (and 5% damping). The maximum value of the ground acceleration is 0.45·g for fundamental periods below 1 s.

The seismic hazard to be taken into account during the construction period of the bridge is not specifically addressed in the mentioned study [36], although some data is provided concerning ground accelerations corresponding to different return periods, with a minimum of T_R = 50 years. This rules out a differentiation of the seismic actions for the different construction stages, as considered for wind actions. Hence, for third party checking of the MSS, a ground acceleration of 0.08 g is adopted for all construction stages, which according to the data provided in [36], corresponds roughly to T_R = 50 years.

6. Conclusions

As denoted by many accidents reported from all around the world, with important consequences in many cases, the use of temporary structures entails considerable risk. One of the aspects to be tackled in view of improving this situation is to provide consistent reliability requirements for the design of such structures. This issue is being addressed in the present paper. Acceptance criteria for structure-related risks to persons obtained in prior studies are adapted to the special circumstances of non-permanent use of a structure. Thereby, the general principle followed is to maintain the same risk levels per time unit as for permanently occupied structures. It is shown that the derived target reliability indices, taking account of the temporary use of construction works, might be significantly higher than the values suggested for permanently used structures.

A case study is then presented to illustrate how the time-dependent, risk-based requirements may be used in practical applications: The third party checking of the movable scaffolding system (MSS) used for erection of the access viaducts of the Pumarejo bridge in Barranquilla (Colombia). The principle construction stages under use of the MSS are identified and the corresponding target reliability indices established and translated into partial factors. These partial factors are found to be up to 15 % higher than the values established in the Eurocodes for reliability class RC2 structures. On the other hand, the representative values for the relevant variable actions, i.e. wind and seismic actions, must also be adjusted to the duration of the different construction stages under use of the MSS.

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