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RELIABILITY OF PRESTRESSED CONCRETE BRIDGE GIRDERS USING FIELD INFORMATION AND THE COMBINED APPROACH

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Abstract. *Field information on live loads and concrete strength is used to assess the reliability of a prestressed precast concrete girder of an existing bridge in Guanajuato State (Central Mexico). A recently developed method, termed the combined approach (CA), is used to perform the reliability analysis. The approach combines two well-known techniques: the first order reliability method (FORM) and the point estimate method (PEM). Information on the bridge design, live load from weigh-in-motion data and compressive strength of concrete cores, was gathered for this study through two research projects. The information is employed to probabilistically characterized the demand and the capacity of the bridge prestressed concrete girders. A numerical scheme is used to obtain the girder bending capacity, and the bending capacity of the point estimates for the reliability analysis, by considering common design practices in Mexico. The use of a numerical method can be required, or more practical, if non-common geometries and prestressed steel and /or reinforcement steel arrangements are used (e.g., non-tension-controlled girders). This implies that the limit state function (LSF) could only be implicitly known, and the FORM may not be feasible, while the Monte Carlo simulation technique (MCS) may require extensive samples. The present study shows the results of the reliability levels for the bridge girder for a range of mean live to dead load effects. This reliability is obtained with information directly gather on field for the bridge under study, for a traffic jam scenario and for a single vehicle passage scenario. It is concluded that the CA can be an adequate alternative to perform the reliability analysis, especially when there is no explicit limit state function (as for instance required in the FORM), and without the need of extensive simulations (unlike the MCS). Some codified design implications are discussed from the resulting reliability levels, and future research for several issues is recommended.*

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1 INTRODUCTION

The reliability analysis of presetressed concrete bridge girders is used to estimate the probability of failure of these elements when subjected to load demands of different kind. The computed probabilities of failure are linked to the reliability index, commonly employed to establish code formats to achieve certain safety consistency. The reliability levels of prestressed precast concrete bridge girders is reported in the literature [1, 2]. However, most of the studies use typical bridge sections, and statistics and probabilistic information from other sources, rather than using existing bridges and deriving probabilistic information from field information and/or real bridge projects expressly selected for reliability studies.

Recent studies on reliability of prestressed concrete beams and bridge girders include sensitivity analysis using updated databases on materials [1], comparison of different standards [2], spatial and time depend reliability under corrosion and/or cracking effects [3, 4, 5], beams exposed to fire [6] or considering creep models [7], and calibration tasks [8], among other issues.

In Mexico, there are also some studies on reliability of prestressed concrete bridges dealing with optimal inspection times considering corrosion [9, 10], which use some local guidelines for designing precast prestressed concrete beams. In this study the AASHTO regulations are adopted [11] to obtain the flexural capacity of the bridge girder, since this is not an uncommon practice among Mexican practitioners, according to one of the authors of this study with experience in the field. Nevertheless, the load factors and live loads are based on previous studies, and weigh-in-motion (WIM) data recorded at highways located at Guanajuato State in Central Mexico.

Other field information that is necessary for reliability studies of existing bridges, is that related to the capacity of the prestressed concrete bridge girders. In the present study, the compressive stress, required in the methods to compute the bending capacity of prestressed members, is derived from concrete cores directly extracted from existing bridges and tested to obtain relevant parameters. The bending capacity of the considered prestressed concrete girder is obtained by considering the equilibrium of the section including, both, the reinforcement steel and the prestressing strands, and a numerical scheme (instead of any formulae, which applicability could be limited to certain cases).

There are several available reliability methods to assess the safety levels of bridge structures [12, 13]. Some of them require the establishment of an explicit limit state function, like the first order reliability method (FORM), or a very extensive number of simulations, like the Monte Carlo simulation techniques (MCS). Reliability indices are obtained by using an approach which can leave aside the use of an explicit LSF, using only a few point estimates. The method is termed combined approach [14], since it combines the use of other known techniques, the FORM and the point estimate method (PEM) [15-18].

The assessment of reliabilities of prestressed concrete bridge girders is important to understand the implicit reliability levels for codified design, the possible impact of loads and resistances for a specific geographic and socioeconomic region, and the design implications.

Therefore, the main objective of this study is to obtain the reliability of a prestressed concrete girder of an existing bridge in Guanajuato, Mexico, subjected to bending, using field information on the demand and the capacity, and the combined approach.

2 FIELD INFORMATION

This section is divided in three parts. First, a general description of selected bridges in Guanajuato for research purposes is briefly reported; then, the recorded and used weigh-in-motion data is outlined; finally, a summary of the tests from concrete cores extracted from the selected bridges is succinctly described.

2.1 Existing bridges

As a part of two research projects financially supported by two Mexican institutions, one to investigate the concrete capacity sponsored by PROMEP (Project "Nuevos PTC", UGTO-PTC-429), and the other one to investigate the live load demands sponsored by CONACYT (Project "Problemas Nacionales 2014", No. 248162), five existing bridges in Guanajuato State in Central Mexico, a key transportation region in the country [19], were selected. Prestressed precast concrete medium span bridges were selected for the research, since these are a very common type of bridges in Guanajuato, and possibly in the whole country [20]; note that bridges of this kind are also very common in other countries, like Mainland China, Hong Kong and the United States [2]. These bridges were also chosen because they are located on (or close to) the highways where the WIM is (or is to be) recorded. Other issues which impacted the selection decision of the bridges were time, distance, available financial support, feasibility to be sampled, among many other aspects, not always as initially planned and too long to be described here.

And attempt was made to get the original project information for each of the selected bridges, but so far only partial information is available. In fact, the bridge selected for the present study, is one of the mentioned five bridges with more complete available information. The structure is a 30 m span bridge, simply supported on abutments, and which superstructure is built with prestressed precast type AASHTO concrete girders, and shown in Figure 1.

Figure 1: Bridge considered in this study.

2.2 Demand

As part of the research project to gather information on the demand due to live loads, traffic surveys of different characteristics are conducted. At the time this study is submitted, although some WIM data is already collected in 2017, it is still not processed and available for its use in the present work. Figure 2 shows WIM recorded during February, 2017; this information will be employed in future research. Therefore, probabilistic information derived from WIM data collected in Guanajuato State and reported in a previous study is used instead [21]. Other surveys (static) were carried out by the Mexican Institute of Transportation (IMT for its acronym in Spanish) and are still not available, but will be also included in future studies.

Figure 2: WIM station installed during 2017.

2.3 Capacity

For the five selected bridges previously mentioned, information on the capacity was obtained by means of another research project. The information consisted on relevant parameters of the precast concrete of the bridge girders. Concrete cores were extracted on field from the prestressed precast concrete bridge girders, and tested in lab to obtain the compressive strength, young modulus and other parameters. For the bridge considered here, Figure 3 shows part of the extraction process and some of the samples before testing.

Figure 3: Extraction on field and retrieved concrete cores.

3 NOMINAL CAPACITY FROM CODE

The nominal bending capacity for a girder from the bridge in Figure 1 is computed. The procedure described here to obtain the capacity is used later to derive the mean flexural moment due to dead and live loads for the reliability analysis. The bridge girders are AASHTO type girders with 34 tendons separated 5 cm away centroid to centroid; the lowest layer centroid is 5 cm above the bottom side of the girder. A schematic section of the girder and prestressing strands is depicted in Figure 4, and the material properties and forces employed to compute the capacity are listed in Table 1. The regular reinforcement steel is distributed along the inside perimeter of the beam (except at the extreme fiber of the bottom flange) with a total area, $A_s = 28.5$ cm^2; this reinforcement is also included in the computing. The nominal capacity is based on the AASHTO code [11] (including the resistance factor, ϕ), since such practice is not uncommon among designers in Mexico, as mentioned previously. Rather than using formulae, the capacity is calculated by following the design hypotheses and section equilibrium as specified in Section 5.7.2 in the code [11]; this approach is preferred, since it is not limited to specific cases (e.g., tension-controlled beams), but is adequate for wider applicability. The nominal capacity after considering that 30% of the prestressing is lost is M_n=4102.62 kN·m (which is equal to the resistant moment, since ϕ=1 for the studied case [11]).

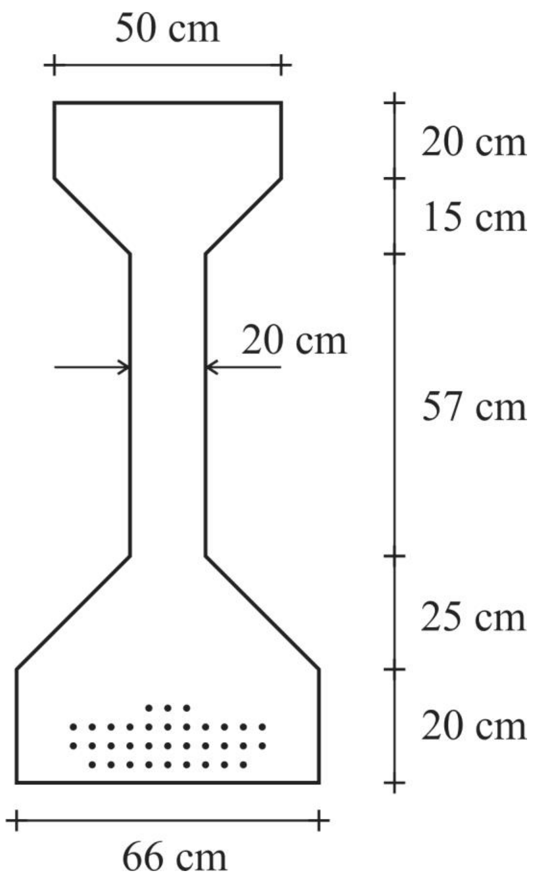

Figure 4: Girder section.

Material	Property	Value
Concrete	Compressive stress	350 kgf/cm² (34.32 MPa)
Steel reinforcement	Yield stress	4200 kgf/cm² (411.88 MPa)
Prestressed reinforcement	Rupture stress	270 ksi (1861.58 MPa)
	Diameter	½ in (12.70 mm)
	Area	98.7 mm²
	Pre–stress force	13100 kgf (128.45 kN)

Table 1: Properties for the considered girder.

4 RANDOM VARIABLES AND LIMIT STATE FUNCTION

The random variables and their probabilistic characterization are listed in Table 2. The random variables in Table 2 are considered independent. Any other variables are taken as deterministic and equal to the nominal values. The moments and probability density functions (PDFs) for the modeling error, B, the reinforcement steel yielding stress, f_y, and the flexural moment due to dead load, D, are based on a previous study [20]. Other variables in Table 2 account for the uncertainty related to prestressing steel ultimate strength, f_{pu}, the prestressing steel area (for each tendon), A_{ps}, and the prestress loss, P_{Loss}, (it is considered that 30% of the prestressing force is lost for a return period over T_r = 50 yr). Since statistics for the prestress are not readily available for the Mexican practice, but the nominal values of Mexican manufactures are very similar to those reported in the literature, they are adopted from (or based on) other works for f_{pu} [6], A_{ps} [1, 9] and P_{Loss} [4, 5].

The statistics for flexural moments due to live load, L, are based on a previous study [21]; they are dependent on span length, not only for single vehicle passage, but also for multiple presence (both are considered). For the bridge in this study the span length is L_{span}=30 m, and lane load is first considered (not impact included; traffic jam scenario [21]). This leads to select the coefficient of variation shown in Table 2.

The PDF and probabilistic moments of the concrete compressive stress, f'_c, is based on the results from testing the concrete cores shown in Figure 3. The mean and coefficient of variation are statistics directly computed from the available samples for the bridge, and are listed in Table 2; since only four samples are available, a Normal PDF is arbitrarily adopted. Other alternative to investigate a possible underlying PDF for the compressive strength, is to use the available data for the five bridges in terms of the mean to nominal values; this strategy may be explored in future studies. Since the bridge is relatively new, no correction for concrete age is carried out; this issue will be also considered in further research.

Random variable	mean	Coeff. of variation	Coeff. of Skewness	PDF
B	1.1	0.10	0	Normal
f'_c *(Mpa)*	35.62	0.052	0	Normal
f_y *(Mpa)*	458.8	0.096	0.301	Lognormal
f_{pu} *(Mpa)*	1,910.26	0.025	0	Normal
A_{ps} *(mm²)*	98.7	0.016	0	Normal
P_{Loss} *(%)*	30	0.30	0.301	Lognormal
D *(kN·m)*	**	0.10	0	Normal
L *(kN·m)*	**	0.069	1.1395	Gumbel

Table 2: Random variables and their characteristics.

Note that the mean dead load effect (flexure moment), m_D, and mean live load effect (flexure moment), m_L, are not defined in Table 2. They are derived under the assumption that the prestressed concrete bridge girder just meets the requirement of codified design. This assumption requires the use of a load format from code; the load format used here is based on the Mexican bridge regulations and a live load model proposed for bridge design in Mexico [21, 22]. This leads to the following expression

$$1.3m_D + 1.95m_L = \phi M_{mean} \tag{1}$$

The right-hand side of Equation (1) is the bending capacity multiplied by the resistance factor, analogous to the nominal bending capacity computed as per the AASHTO code [11], except that mean instead of nominal values are employed. There is not specific procedure referred in the Mexican regulations to obtain the prestressed concrete girder capacity for bridge design [22]; consequently, the prestressed concrete bridge girder capacity is computed with the AASHTO code [11], as previously explained.

The reliability indices reported in the next section are computed for a range of mean live load effect to mean dead load effect ratios (m_L/m_D). Note that by considering a certain value of the m_L/m_D ratio, m_D and m_L can be determined from Equation (1) and used for the reliability analysis.

The LSF can be established as follows

$$g_{CA} = R_{pres} - D - L \tag{2}$$

where the bending capacity of the prestressed concrete girder is a function of several variables, $R_{pres} = f\,(B, f'_c, f_y, f_{pu}, A_{ps}, P_{Loss})$. Since the capacity for the prestressed concrete girder subjected to flexure moments is a random variable, which in turn is a function of several random variables, as mentioned above, the need of a continuous derivable function is required if performing the FORM is of interest. To do this, a closed-form expression is required to compute the bending capacity for prestressed concrete members; alternatively, another technique can be used to carry out the reliability analysis. Since a numerical scheme is used for computing the bending capacity, such capacity can be obtained for a wider range of design cases, but on the other hand, the use of the FORM cannot be directly implemented. In this case, other options (e.g., the MCS) can be used to estimate the probabilities of failure, and so the reliabilities; however, this can be computationally expensive. Therefore, the CA [14] is used in the next section.

Before proceeding to carry out the reliability analysis, it is noteworthy to mention some considerations. It is pointed out that the assumption referred to formulate Equation (1), implicitly considers that other factors, like the multiple lane factor (i.e., the event of more than one lane is loaded in the bridge at the same time), or the girder distribution factor are properly taken into account; these aspects are also related to random variables, and deserve future research. For the probabilistic characterization of the multiple lane factors, the methodology described somewhere else could be followed [23].

It is also noted that the reliability index in the present work, β, is an annual reliability index, since the used statistics for the live load effects are linked to such time period [21].

5 RELIABILITY ANALYSIS

The combined approach is used here, since it takes advantage of the computational economy of the PEM (only 2×n realizations are required, where n is the number of random variables [18]), unlike other techniques (e.g., MCS), and it also takes advantage of the efficiency of the FORM (once the LSF has been properly reformulated as per the CA, so that it is explicitly established).

Table 3 shows the values of the variable combinations resulting from the PEM (for the first part of the CA), to compute the girder bending capacity using the numerical scheme referred in Section 3 above (but not load and resistance factors are involved this time).

Number of realization	Value of each variable (PEM)						*Capacity*
	B	*f'c (Mpa)*	*fy (Mpa)*	*fpu (Mpa)*	*Aps (mm²)*	*PLoss (%)*	*(kN·m)*
1	1.37	458.8	35.62	1910	0.987	30	5900.64
2	0.83	458.8	35.62	1910	0.987	30	3578.69
3	1.1	573.6	35.62	1910	0.987	30	4908.21
4	1.1	357.4	35.62	1910	0.987	30	4575.45
5	1.1	458.8	40.16	1910	0.987	30	4804.01
6	1.1	458.8	31.09	1910	0.987	30	4653.59
7	1.1	458.8	35.62	2027	0.987	30	4945.33
8	1.1	458.8	35.62	1794	0.987	30	4531.60
9	1.1	458.8	35.62	1910	1.026	30	4871.58
10	1.1	458.8	35.62	1910	0.948	30	4606.76
11	1.1	458.8	35.62	1910	0.987	53.4	3552.04
12	1.1	458.8	35.62	1910	0.987	9.3	5703.48

Table 3: Realizations from the PEM and corresponding obtained bending capacities.

The 12 (2×n) realizations of the prestressed concrete bridge girder capacity are also included in Table 3 (last column, bending capacity in kN·m); these values are employed to obtain the first two probabilistic moments of the girder capacity (R_{pres} in Equation (2)) [18]; the mean and coefficient of variation resulted in 4726.96 kN·m and 0.1391, respectively (note that this implies a mean to nominal value of 1.1522 for the bending capacity of the prestressed concrete bridge girder). With the previous information, the procedure established in the CA [14] is carried out, and the reliability levels are computed by using the FORM and Equation (2), except that R_{pres} in not a function of many random variables, but a single, completely determined random variable, as established by following the CA (details can be found in other study [14]). Figure 5 shows the reliability levels for the prestressed concrete girder by using the CA for a range of m_L/m_D values.

From Fig. 5 it can be observed that the annual reliability index is between around 3.6 and 4.4 for a range of m_L/m_D values (dotted line). As reference, note that a target reliability index for 1 year (β_T) equal to 3.75 was employed for calibration purposes in previous studies [21], studies from which the live load effects statistics are adopted for the present work; note further that the same load factors format from the Mexican regulations [22] are used (Equation (1)). The values in Fig. 5 are consistent but moderately higher than those in other studies [20, 21], for different span lengths and for reinforced concrete bridges and steel bridges. In those cases, the annual reliability levels, in average, approximately correspond to an annual target reliability index of 3.75, which in turn is associated to a target reliability index of 3.5 for a service period of 75 years [24]; for the prestressed concrete bridge girder studied here, and for the lane load case, larger reliability levels are obtained, but not significant larger than the β_T = 3.75. Since the statistics of live load effects are span dependent, future studies are recommended to further inspect the reliability levels of prestressed concrete girders for bridges.

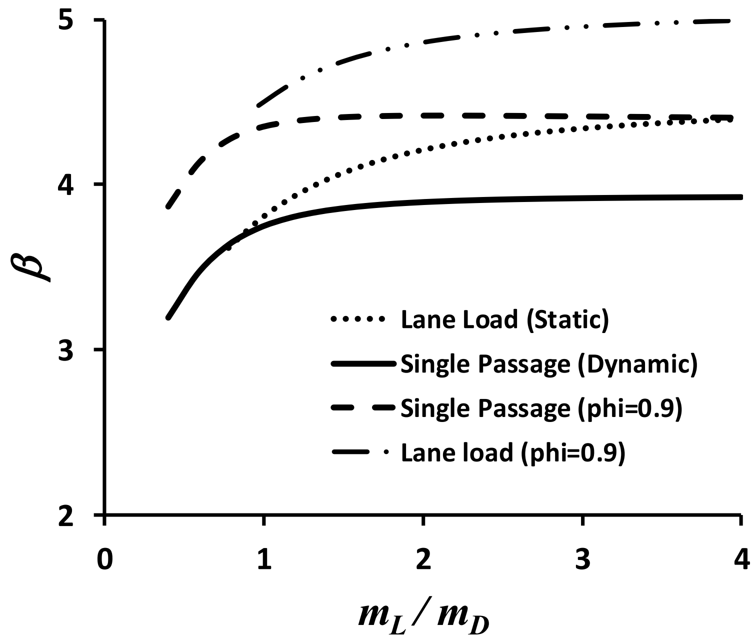

Figure 5: Reliability indices.

Figure 5 also shows the reliability index when a simple consideration on the dynamic live load effect (impact; single vehicle passage scenario [21]) is taken into account. For this purpose, an assumption followed in other study is adopted [1], and Equation (1) is rewritten as

$$1.3m_D + (1.95+0.1)m_L = \phi M_{mean} \tag{3}$$

where an extra 10% of live load effect due to static live load is assumed (i.e., the impact is considered as a fraction of the static live load effect).

The same procedure using the CA is repeated by considering Equation (3), except that the coefficient of variation of L, is not the one in Table 2, but equal to 0.12. This is derived, in one hand, by considering a coefficient of variation equal to 0.065 for L_{span}=30 m, for the case of single vehicular passage [21], which is the relevant scenario for dynamic amplification; on the other hand, to include the coefficient of variation for the dynamic effect, a value is adopted from other work and equal to 0.10 [5]; the previous coefficients of variation are used to derived the coefficient of variation of the total (static plus dynamic) live load effects, under the assumption that the square root of the sum of the squares can be used to compute the total coefficient of variation [25] (like if both effects were normally distributed), and this resulted in the value of 0.12 referred above. It is acknowledged that this is not the most rigorous possible treatment of the dynamic live load effect, and future work is recommended.

The results by including the dynamic effects show that a decrease in the reliability index is exhibit (Figure 5, solid line); this is a consequence of the larger dispersion (in terms of the coefficient of variation) introduced by the dynamic effects in the live load. In fact, values closer, in average, to an annual target reliability level of 3.75 (or 3.5 for a service period of 75 years [24]) are obtained.

A couple more of reliability analyses are performed by using the CA, but considering a ϕ=0.9 (as proposed in other study [21]), instead of the AASHTO strength factor; this is carried out for both, the lane load case and the single vehicle passage. The obtained reliability indices are those also indicated in Figure 5 for the static case (dash-dotted line) and for the dynamic one (dashed line). The used of ϕ=0.9 results in a shifting upwards (in relation to their counterparts as per the AASHTO [11], ϕ=1), increasing the reliability levels for the whole range of m_L/m_D ratios. This may indicate that, unlike the case of steel and reinforced concrete bridge girders, ϕ=1 could be more suitable for prestressed concrete bridge girders, if the target reliability index mentioned above is considered, and the live load models and load factors proposed in a previous work are used [21]; however, more analyses (e.g., by considering other bridge spans, and/or by exploring load factors format as a function of the m_L/m_D ratio [14]) may be convenient for calibration tasks.

As a final remark, it is noted that the CA procedure can be implemented for other LSFs (e.g., shear), and it can potentially be used when a numerical method is required to compute the capacity of an element (e.g., a finite element model), or maybe even of a system, but further research is recommended to investigate such issues.

6 CONCLUSIONS

- The reliability of prestressed concrete bridge girders is assessed using field information and the combined approach (CA). It is pointed out that it is not common to find in the literature the use of field information on loads and strengths, expressively gathered to compute reliabilities (like in this study). Some relevant findings of this study are given below.
- The CA is a simple method to obtain reliability levels of prestressed concrete bridge girders; it is a convenient alternative when a continuous derivable limit state function (LSF) is not available (unlike the FORM), or if an extensive number of simulations (like in the MCS), computationally expensive methods, or complex techniques are not desired.
- When the lane load (static live load; traffic jam scenario) is considered, an annual reliability index between around 3.6 and 4.4 (bending) for a range of m_L/m_D values is obtained for the considered prestressed concrete bridge girder.
- The results by including the dynamic effects show a decrease in the reliability index, compared to the static live load case; this is a consequence of the larger dispersion (in terms of the coefficient of variation) when such effect is considered. For this scenario, values closer to an annual target reliability level of 3.75 (or 3.5 for a service period of 75 years) are obtained for the same prestressed concrete girder.

- When a ϕ=0.9 instead of ϕ=1 is used, the reliability indices (for both, the static and dynamic cases) are shifted upwards; i.e., the reliability levels are increased for the whole range of m_L/m_D ratios. It is concluded that the used of ϕ=1, together with a previously proposed live load model and load factors, could be more suitable for computing the capacity of prestressed concrete bridge girders, if an annual target reliability level of 3.75 (or 3.5 for a service period of 75 years) is of interest.
- The CA could be a valuable alternative for other LSFs and, in general, when a numerical method is involved in computing the capacity of an element (e.g., finite element models), and maybe even in other cases. Further research is recommended in the body of the manuscript, to investigate these and other issues.

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