Human error effect in the robustness of a reinforced concrete bridge

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ABSTRACT: To the bridges failures that have been arising over the years, experts have pointed out as the main cause of failure, human errors, in the design, construction and operation phases. One of the main goals of this paper is the identification of the foremost causes of failure due to human errors in design and construction procedures. Therefore, a bridge failure database that includes several failure cases and a human errors survey will be used to support this line of work. After the identification of some explicit human errors that is believed to be the source of several reinforced concrete bridges failures, a selective analysis using risk indicators, namely, the probability of occurrence and consequence, is performed to choose those that might represent a higher risk for the structural safety. The outcome of five chosen human errors in a specific case study is quantified using a robustness index that will be computed according to the reliability index reduction of the structure due to the damages caused by the human errors, allowing to demonstrate how these errors can have a huge influence in the structural safety. The modelling and the finite element analysis of the structure will be performed using TNO DIANA software, allowing the calculation of the reliability index of the structure damaged by different human errors. Within the COST action TU-1406, the main goal of this work is to give a contribution to the establishment of a roadways bridge quality control plan with higher efficiency in the reduction of bridge failures and their substantial, fatalities and economic loss.

1. INTRODUCTION

The transportation system, as one of the key elements for economic development and the fulfilment of human happiness, has always been a valuable asset for societies. Nevertheless, the transportation system depends very often on connections provided by roadway, railway and footway bridges. Thus, these infrastructures have a crucial role to play in the transportation network, being responsible for tremendous consequences when wrongly managed, as revealed in the literature (Scheer 2010) and the daily news.

To improve the safety of bridges is first required, the documentation of the main source of the uncertainties that have been leading to their failures. Relying on a bridge failure database, that to the author's knowledge, is one of the most completed available database, developed by (Syrkov 2017) with more than 450 worldwide bridge failure incidents from 1966 to 2017 and covering the leading causes of failure (Figure 1), is inevitable the conclusion that the human errors are the primary source of uncertainties leading to bridges collapse.

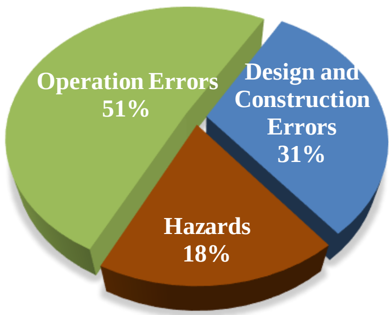

Figure 1 – Leading causes of failure of reinforced concrete bridges (Syrkov 2017)

2. RISK ANALYSIS OF DESIGN AND CONSTRUCTION ERRORS

The design and construction errors are a vast subject and when it is comes to be defined explicitly, the engineers might find themselves very confuse in the definition of their boundaries and their identification in the complex conception process of a bridge. In this the paper, the human error is defined as being any design, construction and operation errors that don't exceed the currently available engineering knowledge, and which took place due to poor working conditions, lack of training, supervision and check-up procedures. These errors or uncertainties are not covered by the safety factors of the current standards. A similar definition of human error is given by (Tylek et al. 2017) and (Brehm et al. 2018). The human errors usually assume different shapes and magnitudes thus they represent different risks and they might also represent different risks for different structures when compared to each other. Therefore, it is vital the identification of those that may well represent a greater risk, for better quality control and more effective mitigation. In order to identify more than a few design and construction errors with some impact in the structural serviceability and safety a brainstorming meeting with several experts in the sector was set. A total of 20 design and 29 construction errors were identified towards a prestressed reinforced concrete bridge. Afterwards, these errors were compiled and disseminated on a very well-structured survey, in order to assess, qualitatively, each one of them according to their probability of occurrence and the consequence. The results of the survey were treated according to the analytical hierarchical process bestowed by (Goepel 2013), allowing to rank the errors according to the overall risk they represent for the structure. The wide-ranging identification of all the errors and the complete analysis carried out can be found in (Galvão et al. 2018).

3. CASE STUDY – NUMERICAL ANALYSIS

The longitudinal profile of the case study is a three-span bridge of 18 *m* + 27.8 *m* + 18 *m*, consequently with a total length of 63.8 *m*. The bridge deck is connected to two piers by means of a transversal beam with 3 *m* height and the connection to the abutment is carried out by simply supported transversal beam with a height of 1.9 *m*. The piers are supported by a deep spread foot foundation, built more than 3.0 *m* below the road platform.

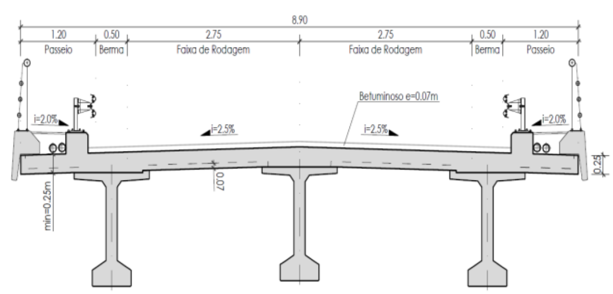

Figure 2 – Transversal deck cross-section

The representative transversal cross-section of the deck comprises a set of three pre-cast I-beams with a total height of 1.5 *m*. The beams were pre-cast with C45/55 concrete and prestressed by means of pre-tensioned strands in its upper and lower flange, while they are under simple support static condition. Therefore, the continuity of the deck over the piers is only ensured by the passive reinforcements in the cast in-situ slab and in the pre-cast beams, hence, no hyperstatic stress is developed on the deck due to the prestress forces. For the elements cast in situ a C30/37 concrete, was used. The concrete slab has 0,25 *m* of thickness and 8,9 *m* of width, giving rise to a cross-section whose maximum height is 1,75 *m* (Figure 2).

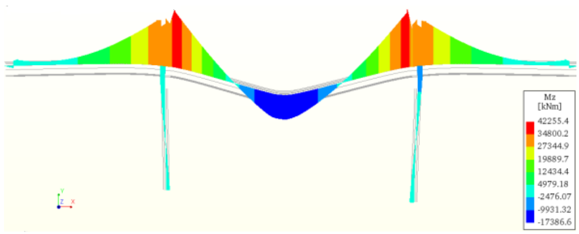

Figure 3 - Bending moment distribution for maximum load factor

The numerical model of the case study is shaped using a three degree of freedom beam element in order to reduce the computational time of the numerical non-linear analysis, and consequently the computation cost of the probabilistic analysis to be performed. To model the deck cross-sections, an equivalent cross-section to the original one was determined due to some limitations of the finite element software, when it comes to 2D numerical models (TNO DIANA 2008). The constitutive models used to describe the tensile and compressive behaviour of concrete and the reinforcement comes respectively from the Eurocodes (NP EN 1992-1-1 2008) and (EN 1992-1-2 2010). The load bearing capacity of the structure is verified according to the load model 1 (LM1) of (EN 1991-2 2003). The load distribution given by the LM1 when properly transformed to a longitudinal load, will correspond to a uniformly distributed load of 47,75 kN/m and to two concentrated loads of 500 kN spaced apart by 1.2 m. The positioning of the loads is performed according to the location of the critical section which in a first analysis was shown to be the mid-span section of the central span. According to the static system, the bending moment influence line of the critical section if draw leading to the positioning of LM1, in order to amplify its bending moment effect (Figure 3). With the numerical model set according to the real case study conditions, the load-bearing capacity of the virgin structure, based on the mean value of the resistance parameters, is determined through an incremental load procedure that traces the non-linear behaviour of the structure, until its failure.

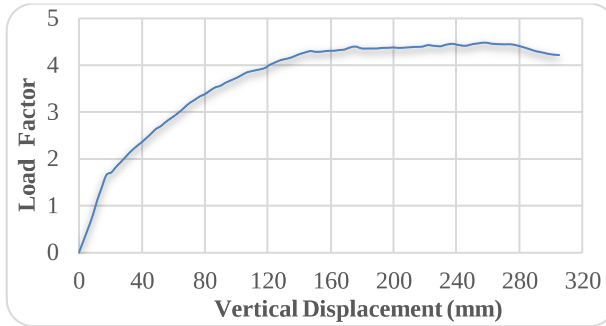

Figure 4 - Vertical displacement of the critical cross section with load incrementation

The failure of the system occurs due to the concrete crushing in the deck critical section after the yielding of the reinforcement and the redistribution of the bending moment, for a load factor of 4.5 (Figure 4).

4. PROBABILISTIC ANALYSIS

The probabilistic analysis takes into account several uncertainties related to the structural real conditions, such as geometrical uncertainties, mechanical uncertainties, material uncertainties, numerical model uncertainties and action model uncertainties. All these uncertainties are taken in to account through a group of random variables characterized by several well established probabilistic distribution that leads to the computation of the structural system failure probability or reliability (JCSS - 2001a). Aiming the achievement of the case study reliability index, all the random variables that are part of the numerical problem was identified and statistically characterized according to literature (Table 1). To every random variable was assigned an identification number (ID) used to introduce the results of a sensitivity analysis performed according to (Matos et al. 2016), which aims the reduction of the random variables involved in the probabilistic analysis. According to this importance factor given by the chosen approach, the random variables with highest impact on the load-bearing capacity of the structure are identified. A threshold value of 10%, for the importance factor, is considered to identify the random variables with high influence on the structural response of the case study. Thus, they are, the compressive strength of the concrete, the thickness of the deck slab, the area of the longitudinal reinforcement and the ultimate yielding stress of the ordinary and prestressing reinforcement. However, the yielding stress of the ordinary reinforcement is the most influential of all random variables (Figure 5). In order to determine the reliability index of the case study, the Latin hypercube method was implemented according to (Choi et al. 2007), through a developed Matlab script to determine the maximum load factor of the 100 samples, generated by the method, using TNO DIANA software with its non-linear analysis tools.

Table 1 - Random variables and their statistical properties used in the probabilistic analysis

ID	Description	Random Variables	Notation	Nominal Values	Bias	COV	Reference
1	C30/37	Compressive strength	f_{cm}	30 MPa	1.27	12%	*Wisniewski (2007)*
2		Tensile strength	f_{ctm}	2.0 MPa	1.45	20%	*Eurocode (2002), Wisniewski (2007)*
3		Modulus of elasticity	E_{cm}	33 GPa	1.00	8%	*Wisniewski (2007)*
4		Deck slab thickness	e	25 cm	1,00	3,5%	*Wisniewski (2007)*
5	C45/55	Compressive strength	f_{cm}	45 MPa	1,18	9%	*Wisniewski (2007)*
6		Tensile strength	f_{ctm}	2.62 MPa	1.45	20%	*Eurocode (2002), Wisniewski (2007)*
7		Modulus of elasticity	E_{cm}	36 GPa	1.00	8%	*Wisniewski (2007)*
8	S500	Yielding and ultimate strength	f_{sy} e f_p	560 MPa	1.12	5.4%	*JCSS (2001)*
9		Reinforcement cross section area	A	--	--	2%	*JCSS (2001)*
10	S1670/1860	Yielding and ultimate strength	f_{sy} e f_p	1258 MPa	1.04	2.5%	*JCSS, (2005), Wisniewski (2007)*
11		Pre-stress tension	σ_p	1087 MPa	1.00	1.5%	*Wisniewski (2007)*
12	C30/37 e C45/55	Concrete self-weight	γ_c	25 kN/m3	1.03	8%	*JCSS (2001) Wisniewski (2007)*

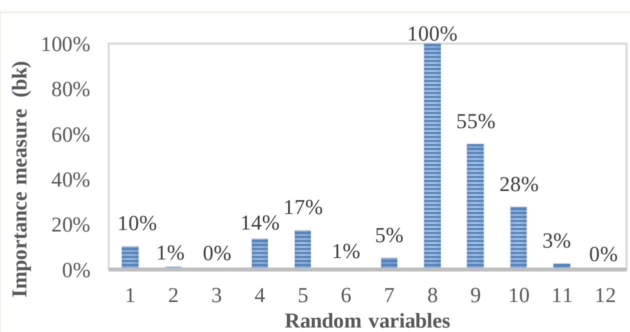

Figure 5 – Random variables sensitivity analysis

With the output results of each Latin hypercube sample, the probabilistic distribution of the structure resistance is obtained according to the uncertainties that surround the numerical problem (Figure 6). Since the resistance of the structure is given by a multiplication factor of the LM 1, the probabilistic distribution of the load model can be presented as a unit factor of the resistance curve

(Figure 7). It's important to highlight here that numerical model uncertainties were not taken into account in this paper. Future works will implement these epistemic uncertainties.

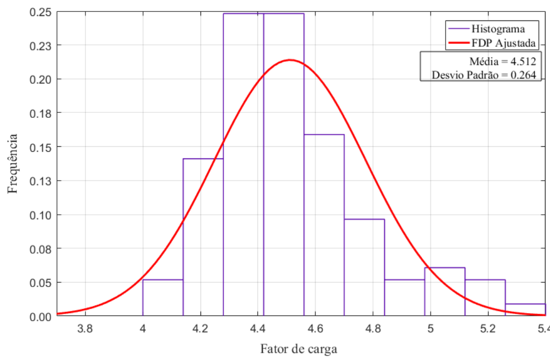

Figure 6 – Probabilistic distribution of the structure resistance

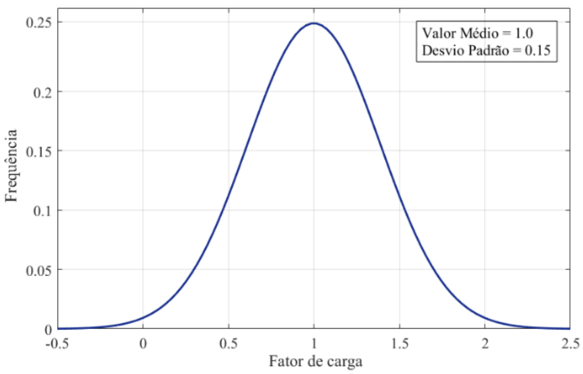

Figure 7 – Load model 1 probabilistic distribution

The coefficient of variation of the load model 1 was considered to be 15% according to (Wisniewski 2007) and (Campos e Matos 2013). Nevertheless, the ideal solution would be to obtain the probabilistic distribution of the load through a histogram given by monitoring data of the crossing vehicles on the bridge.

Defined the probabilistic curves that characterize the resistance and the load uncertainties, the formulation presented in (NP EN 1990: 2009) is used to compute the structural reliability index, where μ_R and μ_s respectively represent the mean value of the resistance and the load, and σ_R e σ_S respectively represent the standard deviation of the resistance and the load. Therefore:

$$\beta = \frac{\mu_R - \mu_s}{\sqrt{\sigma_R^2 + \sigma_S^2}} = \frac{4.512 - 1}{\sqrt{0.264^2 + 0.15^2}} = 11.57$$

By comparing the value of the reliability index obtained with the target reliability index given in (FIB 2003), it can then be stated that the case study is in an excellent safety condition. Considering that the entire modelling procedure is based on the design report, without taking into account any kind of damage or degradation that the structure might be exposed, the obtained reliability index value is reasonable. It should also be stated here that the analysis carried out is relative to the whole system, thus considering the bending moment redistribution through the structural system. In other words, the analysis is not limited to a section resistance, as usual, where the values of the reliability index are usually of lower orders.

5. ROBUSTNESS ASSESSMENT

Structural robustness is defined by (EN 1991-7 2003) as the ability of a structure to withstand events such as fires, explosions, impact or consequences of human error without being damaged to an extent disproportionate to the original cause. Hence, the robustness analysis takes for granted the quantification of the proportionality between the impact or consequence of certain damage and its magnitude. Within the scope of this paper, the impact of certain damage caused by a human error is measured through the global variation of the structure reliability index. In order to perform the structure robustness assessment, a group of three design error (DE) and two construction error (CE) is considered. These errors were nominated from an extensive list of error, highlighted in chapter two, according to the following criteria: (i) the ease of modelling the damage caused by the error; (ii) the adaptability of the error to the case study; and (iii) the risk associated with each error (Table 2). The damages caused by the construction and design error are modelled deterministically according to the numerical parameters and the magnitude presented in Table 3. The magnitude or severity of the error is presented in Figure 8 by means of relative values (percentages) along with its impact, in order to normalize and simplify the interpretation of the results.

Table 2 – Damages used for robustness assessment of the structure

Damages	**Errors leading to the damages**	**Error type**
1	Error in dead load quantification	DE
2	Error in the definition of the reinforcement cross-section area	DE
3	Error in the definition of the soil-structure interaction (support conditions and differential settlements)	DE
4	Error due to insufficient prestressing force	CE
5	Error in the manufacturing requirement of the ordered concrete, giving rise to a concrete of low quality	CE

Table 3 – Numerical parameters and damages magnitude used for the robustness assessment

Damages	**Numerical Parameters**	**Damage Magnitude**			
Damage 1	G_{k1} = 98.97 *kN/m*	1,15 G_k	1,45 G_k	1,75 G_k	2,00 G_k
	G_{k2} = 56.16 *kN/m*				
Damage 2	$A_{s1,\,sup}$ = 54.3 cm^2	0,85 A_s	0,55 A_s	0,25 A_s	0,0 A_s
	$A_{s1,\,inf}$ = 49.8 cm^2				
	$A_{s2,\,sup}$ = 142.7 cm^2				
	$A_{s2,\,inf}$ = 138.2 cm^2				
Damage 3	d_s	5 *cm*	10 *cm*	15 *cm*	20 *cm*
Damage 4	σ_{p1} = 1046.25 *MPa*	0,85 s_p	0,55 s_p	0,25 s_p	0,0 s_p
	σ_{p2} = 1087.05 *MPa*				
Damage 5	$f_{cm,\,C30/37}$ = 38 *MPa*	0,85 f_{cm}	0,55 f_{cm}	0,3 f_{cm}	0,2 f_{cm}
	$f_{cm,\,C45/55}$ = 53 *MPa*				
Multiples Damages	G_{k1} e G_{k2}	1,15 G_k	1,45 G_k	1,55 G_k	
	d_s	5 *cm*	10 *cm*	11 *cm*	
	$f_{cm,\,C45/55}$ e $f_{cm,\,C30/37}$	0,85 f_{cm}	0,55 f_{cm}	0,45 f_{cm}	

To accomplish the robustness assessment of the structure each damage was specifically introduced in the numerical model, following the safety condition evaluation by means of the reliability index. To model the Damage 1 the permanent load was increased throughout the structure. The Damage 2 was modelled by decreasing the upper and the lower deck slab reinforcement cross-section area. The deck slab reinforcement was chosen over the pre-cast beams because it was conceived in a more controlled environment which represent a lower probability of error when compared to the placement of the reinforcement on site. The soil-structure interaction (Damage 3) was modelled considering differential settlements of the piers. The following damage is modelled through the decrease of the prestress forces applied to pre-cast "I" beams cables. It should be noted here that the prestressing reinforcement area was not reduced, which usually happens when it is attacked by corrosion and can be found in the common literature.

As expected, there is a more or less marked drop of the reliability index with increasing error severity (Figure 8). Exceptionally for Damage 4, there is an increase in the reliability index. This damage outcome on the mean maximum load-bearing capacity of the structure is minimum, representing a total loss of 3.5% throughout the entire damage magnitude. However, there is a marked decrease of the standard deviation, i.e. an increase in the certainty of structure behaviour, which eventually pay off the minimum loss of load bearing capacity, thereby, increasing the reliability index. The loss of prestressing stress, despite have been shown to be favourable to the structure safety condition, taking into account the bending moment ultimate limit state it's not for the structure serviceability.

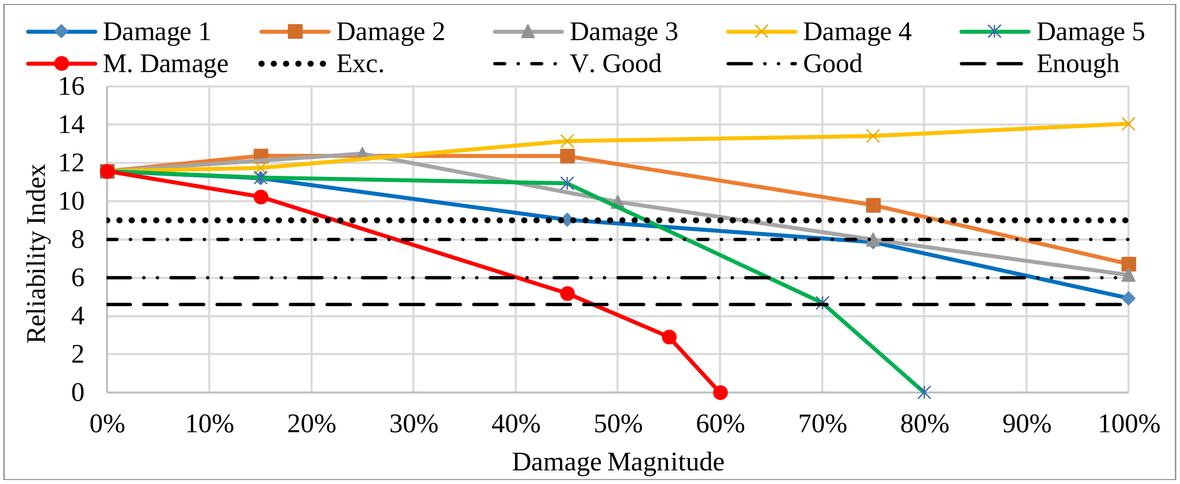

Figure 8 – Reliability index reduction caused by the damage magnitude increase

This calls into question its decompression limit state, thus leading to larger cracks since the structure will be under higher tensile stresses.
The computation of the robustness index comes from the normalization of the reliability indexes, relatively to the highest reliability index associated with each damage, in order to obtain the robustness index presented by (Cavaco 2013). The formulation presented by Cavaco, when compared to most formulation from the literature, it gives a global evaluation of the impact of a damage since it takes into account its influence for different magnitudes through the quantification of the area below the normalized chart. Unlike Cavaco's index, the robustness index is usually computed for specific damage magnitude. The computation of the robustness index was performed considering two damage magnitude limits, one at 45% and the second at 100%. In Table 4 is found the robustness index obtained for each damage according to the previously established limits and their ranking position (Rk). The decrease of the structure reliability index for Damage 5 exhibit to distinct behaviours, a small impact for damages magnitude below 45% and huge decrease on structure reliability for higher damages magnitude. Therefore, it might look like a neglectable error for small damages magnitude but has a tremendous impact for higher magnitude. In this sense, the importance of the proposed sensitivity analysis is demonstrated here since in this situation a punctual evaluation could lead to illusory conclusions.

Table 4 – Robustness Index results

	$I_R^{100\%}$	**Rk 100%**	$I_R^{45\%}$	**Rk 45%**
Damage 1	76,7%	2	91.1%	1
Damage 2	88,1%	4	98.9%	5
Damage 3	78,7%	3	93.1%	3
Damage 4	91,7%	5	92.6%	2
Damage 5	62,4%	1	96.7%	4
Multiple Damages	38.2%		75.7%	

6. CONCLUSIONS

The impact of human error should be measured in three domains: (i) the isolated impact of an error in the early life of the structure (virgin reliability); (ii) the impact of accumulated damages (multiple damages effect); and (iii) its impact associated with the degradation of the structure, or as part of the acceleration of the degradation process. However, it is also found that the whole evaluation is extremely dependent on the magnitude of the error in question.

In cases where the accumulation of some errors does not bring the structure to its collapse, it is important to evaluate its impact on the serviceability over the life of the structure, since the premature failure of a service limit state due to errors in design and construction, is also one of the countless repercussions of human errors in the failure of structures.

7. ACKNOWLEDGMENTS

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