A Simplified Framework for Reliability Assessment of Prestressed Concrete Bridge Girders Under Travelling Loads in Dynamic Regime

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ABSTRACT: Assessing the reliability of prestressed bridge girders is paramount to keeping transportation infrastructure functional. Classical structural reliability assessment requires computing the demand and capacity of the components of interest. In this study, a simplified approach for travelling loads on bridges in dynamic regime is used to calculate the demand in the girders in terms of bending moment and shear force. The structural demand is then compared with the corresponding capacity values computed by accounting for the ageing of the construction materials at different times over the life cycle of a bridge. A numerical fiber-based modelling approach is adopted to compute the ultimate bending capacity of the prestressed girder; a code-based approach is adopted for computing the shear capacity. The main epistemic uncertainties are propagated with a simple Monte Carlo simulation. An existing Italian reinforced concrete viaduct is presented as a case study. Results show that the proposed simplified approach is acceptable for assessing structural reliability along the asset life cycle.

1. INTRODUCTION

There is an urgent need to assess and retrofit ageing/obsolete highways infrastructure, e.g., bridges, exacerbated by climate change effects (Nasr et al., 2020). Highways are crucial for national progress and wealth creation and must be well maintained. However, ageing networks are likely to succumb to wear and tear and adverse weather effects. Also, given the increasing traffic volumes due to larger lorries and autonomous electric vehicles, more bridges may be restricted in the future (Pugliese et al., 2022).

Structural reliability methods offer an efficient way of assessing the health of infrastructure over its life cycle, accounting for all relevant uncertainties, by simply comparing accepted and actual probabilities of failure (P_f) (Frangopol et al., 2021). Such methods also allow to define optimal maintenance plans that must be applied to keep prescribed performance levels (Frangopol and Liu, 2019). Such maintenance plans are even more critical when dealing with existing prestressed reinforced concrete structures designed with obsolete design codes (Calvi et al., 2019).

Classical reliability analyses consist of assessing the performance of a structural system by comparing the demand (D) and the capacity (C) for each component of the whole system (Cornell, 1969). This paper presents a conventional structural reliability analysis for an existing viaduct made of prestressed concrete girders described in Scibilia and Giancontieri (2018). Herein, the capacity of a prestressed bridge girder is computed using a mix of numerical models and code-based approaches; specifically, the methodology proposed by Pugliese et al. (2022) is extended to the case of prestressed reinforced concrete elements. A simple approach is used to account for degradation phenomena and quantify the reduction of both longitudinal and transversal reinforcement rebar area due to corrosion (Rodriguez et al., 1996). As for the demand, the travelling load framework proposed by De Risi (2022) is employed. This simplified approach allows easy implementation in conventional finite element software of travelling loads in dynamic regime.

Epistemic and aleatory uncertainties (Der Kiureghian and Ditlevsen, 2009) are considered hereafter. The epistemic uncertainties are mainly related to capacity. Specifically, the material properties (and their statistical interpretation) presented in Scibilia and Giancontieri (2018) are used to characterise concrete, steel, and tendons. The aleatory uncertainties are mainly related to the demand. In this study, the weigh-in-motion database presented by Guo et al. (2012) is adopted to simulate the travelling vehicles loading across the bridge.

A Monte Carlo simulation is employed to propagate the uncertainties and to compute the distributions of the demand and the capacity for the girder beam in terms of bending moment and shear force. A safety margin formulation is adopted to assess the failure probability (Nowak and Collins, 2012).

Results show that brittle failure is the critical failure mechanism, and maintenance operations preventing corrosion of stirrups are essential for precast beams that may suffer from shear failure.

2. CASE STUDY

The Akragas highway viaduct in Sicily, Italy, is used as a case study. Figure 1 shows the mid-span cross-section of the bridge and the lateral and top view of a single girder. The geometrical features of the bridge and the material properties are presented in Scibilia and Giancontieri (2018). The viaduct is about 1.4 km long; the deck is simply supported and spans 35 m between piers. The deck comprises three prestressed reinforced concrete girders, equally spaced at 3 meters, joined by five transversal coupling beams, two at the two ends and the others at one-fourth, one-half, and three-fourth of the span. The transversal beams guarantee the joint torsional behaviour of the deck (Courbon 1976, Figure 1b). The girders are also connected by precast slabs supporting the road. The geometrical and mechanical characteristics of the equivalent beam used to model the deck are provided in De Risi (2022). The vertical and torsional vibration frequencies of the deck are 3.50 Hz and 1.76 Hz, respectively. Figure 1c shows the geometrical feature of the tendons within the beam. The longitudinal shape of the beam is trapezoidal; tapered sections are present close to the support.

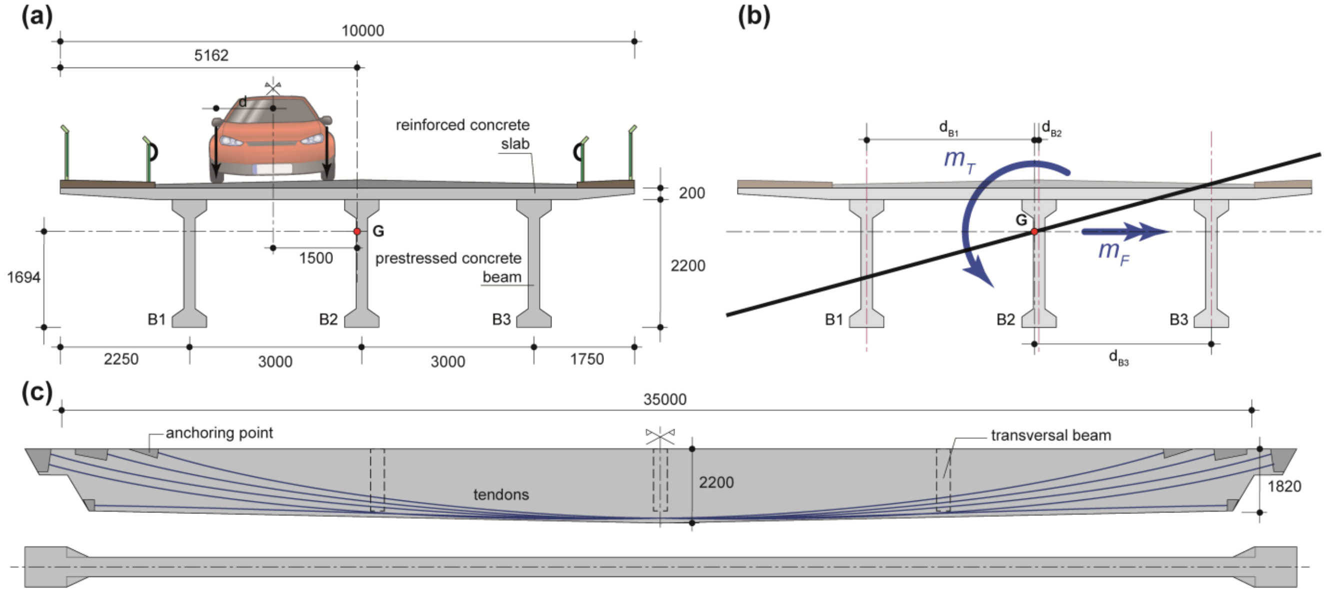

Figure 1: (a) Cross-section of the bridge deck. (b) Typical scheme to assess the effects on the external girder. (c) Side and top views of the prestressed concrete girder beams. Dimensions in mm.

This study will focus mainly on the external beam B1 as, due to torsional effects, it will be subjected to larger excitations due to traffic loading.

3. CAPACITY

Figure 2 shows the cross-section details of beam B1 in terms of geometry and reinforcement for both the mid-span and the support sections. The structural capacity is assessed in terms of bending moment (ductile mechanism) and shear force (brittle mechanism). The concrete mean compressive strength f_c is 34 MPa; the standard deviation is 3.78 MPa. The yield strength of the ordinary mild steel reinforcement f_y is equal to 535 MPa; a coefficient of variation of 10% is adopted for this parameter. The mean tendons tensile strength f_{yp} is equal to 1757 MPa; a 2% is adopted as the coefficient of variation in this case.

Ageing phenomena have been implemented according to Pugliese et al. (2022). The median values 12 years, 20 years, and 54 years are identified as the cracking initiation time, average cracking time, and spalling time, respectively. These times correspond to cracking values of 0.05 mm, 0.30 mm, and 1.67 mm. The corresponding reduction of reinforcement area due to corrosion is assessed using the approach proposed by Rodriguez et al. (1996).

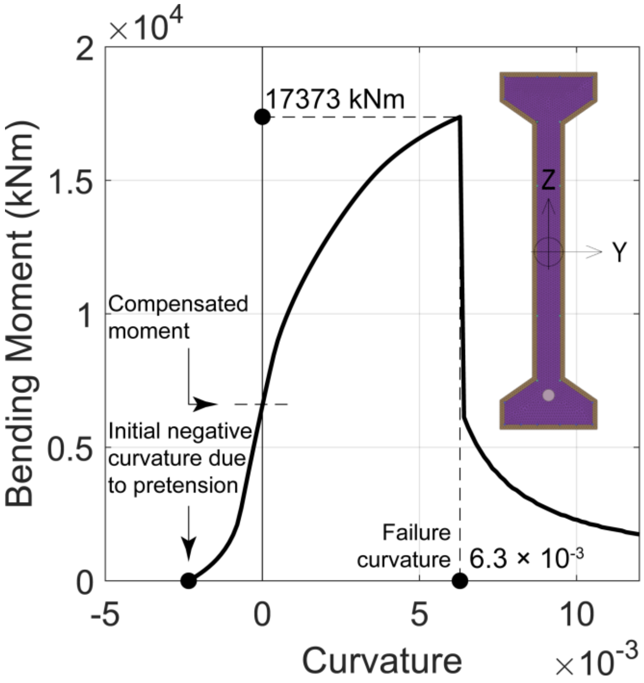

Figure 3: Moment-curvature for the mid-span cross section.

Figure 3 shows the moment-curvature computed for the mid-span prestressed concrete cross-section. Such a plot is computed using the mean material properties, and it is derived employing a fiber-based modelling in OpenSees (McKenna 2011). It is worth mentioning that the initial prestress is modelled using an initial strain material for the tendons.

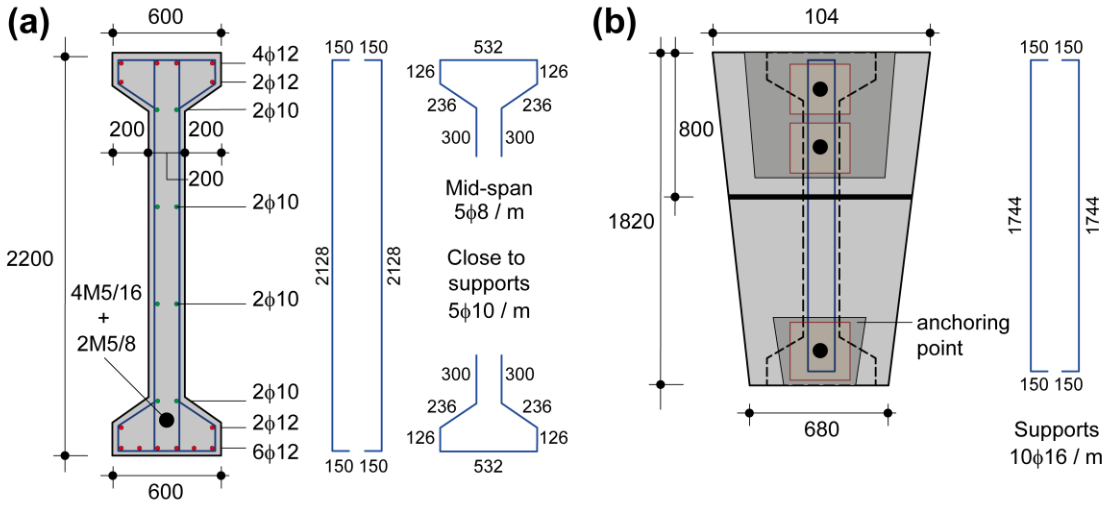

Figure 2: Prestressed beam cross-section with longitudinal and transversal reinforcement at (a) midspan and (b) close to supports. Dimensions in mm.

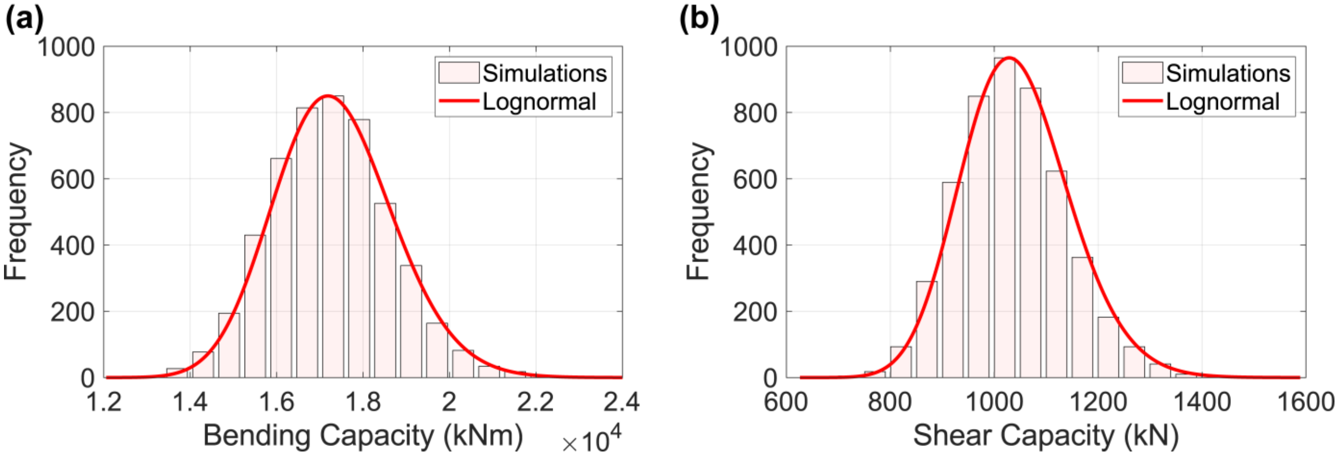

Figure 4: Realisations of the capacity values and fitting in terms of (a) bending moment and (b) shear force.

The initial strain is computed considering an initial stress of 1200 MPa, typically adopted by the designer for this specific typology of structures. A 25% reduction of the initial stress is considered to account for friction and rheological behaviour of the concrete.

The shear capacity is computed using the formulation proposed by Eurcode 2 (EN 1992-1-2, 2004). The capacity is assessed at 1.5 m from the support, where 5ϕ10/m 2-leg stirrups can be found and where the section is not trapezoidal but I-shape as illustrated in Figure 2b.

Figure 4 shows the distribution of the cross-section capacity both in terms of bending moment and shear capacity. A total of 5,000 simulations have been performed to propagate the uncertainties in the different capacity models. The histograms are representative of the realisations. A lognormal fit is found to be the perfect distribution for both capacity mechanisms.

4. DEMAND

The structural demand on the system is computed in terms of bending moment at the midspan and shear force at the supports. In this study, the simplified computational framework proposed by De Risi (2022) is adopted to model traffic loads on the viaduct in a dynamic regime. Such an approach can be implemented/integrated into linear and nonlinear analyses using structural finite element codes, e.g., OpenSees (McKenna, 2011). Specifically, the path of a generic vehicle crossing the bridge is discretised and transformed into force-time histories acting on specific locations of the structural model for specific time windows. The main simplification is modelling the travelling load as a simple travelling massless force in a dynamic regime. It is well known that any traffic load should be modelled rigorously as a travelling force, a system of masses, and dashpots (Alexander & Kashani, 2018; Frýba, 2013). Such a simplification was proven acceptable for the specific range of vehicle masses and velocities involved in this paper.

Such an approach allows for modelling traffic in a probabilistic manner. Deterministic analyses may not be any longer suitable for the assessment of existing bridges since they neglect the randomness of the traffic flow, which is inherently stochastic (Lipari et al., 2017) for both frequencies (Crespo-Minguillón and Casas, 1997) and magnitude of the loading (OBrien et al., 2009) and the dynamic interaction between vehicle and bridge. In this study, the weigh-in-motion database presented by Guo et al. (2012) is employed to simulate a realistic traffic flow of 5,000 vehicles on a single lane. Once the minimum and maximum allowed velocities are defined, the traffic is generated in a stochastic manner, avoiding the collision between two subsequent vehicles. Figure 5 shows an example of time history results in terms of bending moment and shear force.

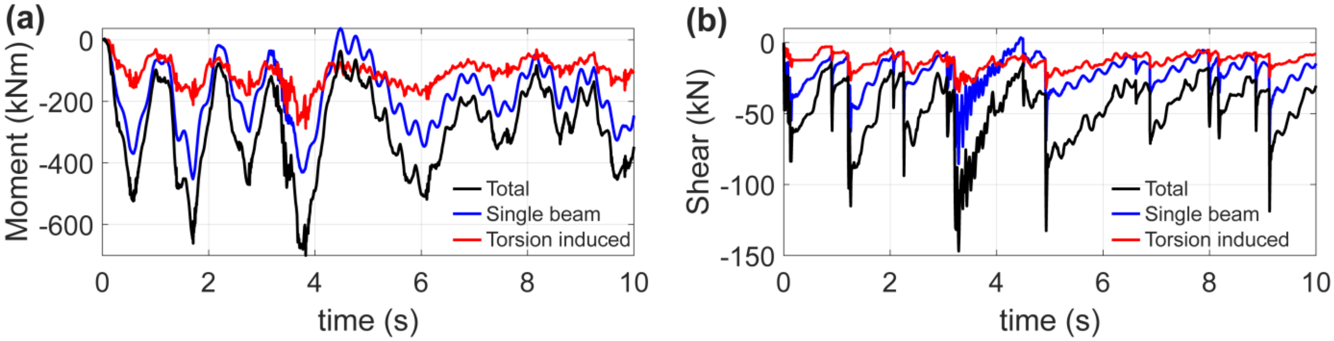

Figure 5: 10-s time history of (a) bending moment and (b) shear force for beam B1 due to traffic loading only.

Both the total values and the breakdown of the bending moment and shear are presented. The biggest contribution to the total action is the bending moment and shear on B1; the torsion increases values significantly. Figure 6 shows the probability plot of the maximum moment and shear in beam B1 due to the 5,000 vehicles individually. The values are distributed according to a Gumbel distribution, which is generally deemed suitable for describing extreme value data such as traffic-induced stresses (Enright & O'Brien, 2013). .

The fitted Gumbel distributions can be used to identify the bending moment and the shear corresponding to a return period of 75 years, which AASHTO (2012) defined as a reference for bridges (in this case, 2290 kNm and 408 kN due to traffic only). However, in this study, these two Gumbel distributions will be used to solve the classical structural reliability problem for the bridge at hand in combination with the two distributions of the capacity presented earlier. The self-weight of the system is added as a constant.

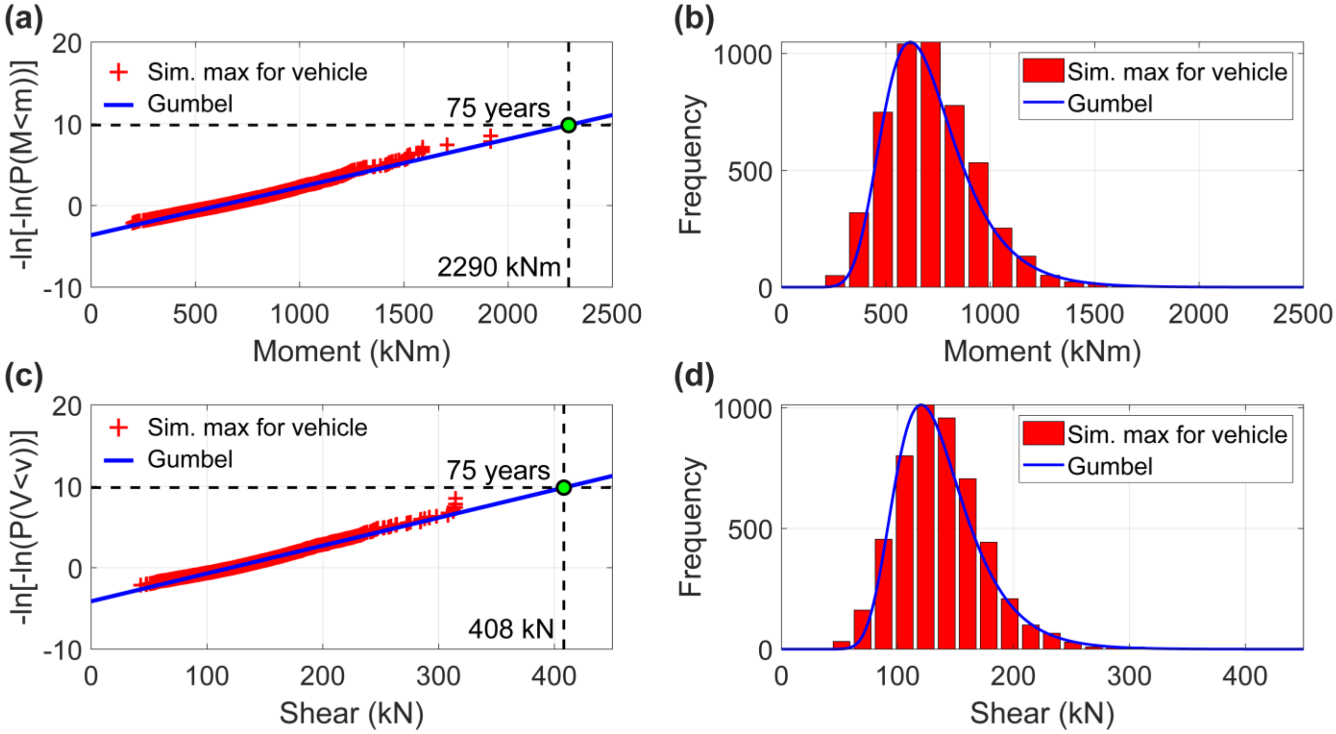

Figure 6: (a) and (c) Probability paper plots of the maximum (negative) bending moment and shear force due to the crossing of 5,000 vehicles. (b) and (d) Realisations of the demand values and Gumbel fitting in terms of bending moment and shear force, respectively.

5. RELIABILITY

The distributions of capacity and demand for both the ductile and the brittle mechanisms are employed to compute the probability of failure using a simple safety margin formulation as limit state function g:

$$g = C - D \tag{1}$$

$$P_f = P(g \leq 0) \tag{2}$$

Several approaches can be used to compute the probability of failure, e.g., numerical integration, simplified analytical solutions, and Monte Carlo simulations. In this study, a Monte Carlo approach is employed.

Specifically, the capacity and the demand have been characterised by a Lognormal and a Gumbel distribution, respectively. Therefore, for each considered mechanism, it is possible to simulate capacity and demand values and derive the distributions of the safety margins. Figure 7 shows the safety margin values obtained by performing 10^8 simulations for both the ductile (Figure 7a) and fragile (Figure 7b) mechanisms. The probability of failure can be derived as the ratio between the number of safety margin values lower than zero and the total number of simulations:

$$P_f = \frac{N_{C-D \leq 0}}{N_{Simulations}} \tag{3}$$

Results show that the brittle mechanism is the only one for which it is possible to compute meaningful (i.e. >0) probability of failure. More specifically, it has been observed that no failure can be observed at the construction time (t = 0 years) and at the cracking initiation time (t = 12 years). At t = 20 years (average cracking configuration), a negligible probability of failure of 2×10^{-8} is computed. Eventually, at t = 54 years (corresponding to cover spalling), the probability of failure rises to 1.03% (Figure 7), a value corresponding to a reliability index β of 2.32. Such value is not satisfactory with respect to the indication provided by the Eurocode (CEN 2002).

6. CONCLUSIONS

This work presented a simple reliability analysis for the deck of an existing Italian bridge. The main focus has been a single external prestressed girder, for which some details were available from the literature.

The main emphasis has been the adoption of simulated traffic loadings using a dynamic finite element implementation. Also, a simplified approach is used to model ageing phenomena.

The key conclusion is that for prestressed concrete girders designed with obsolete codes and guidelines, it is essential to make sure that maintenance is regularly done with the scope of safeguarding transversal reinforcement governing brittle failure.

Future work must be done around uncertainties associated with prestress, and better models should be implemented for material ageing.

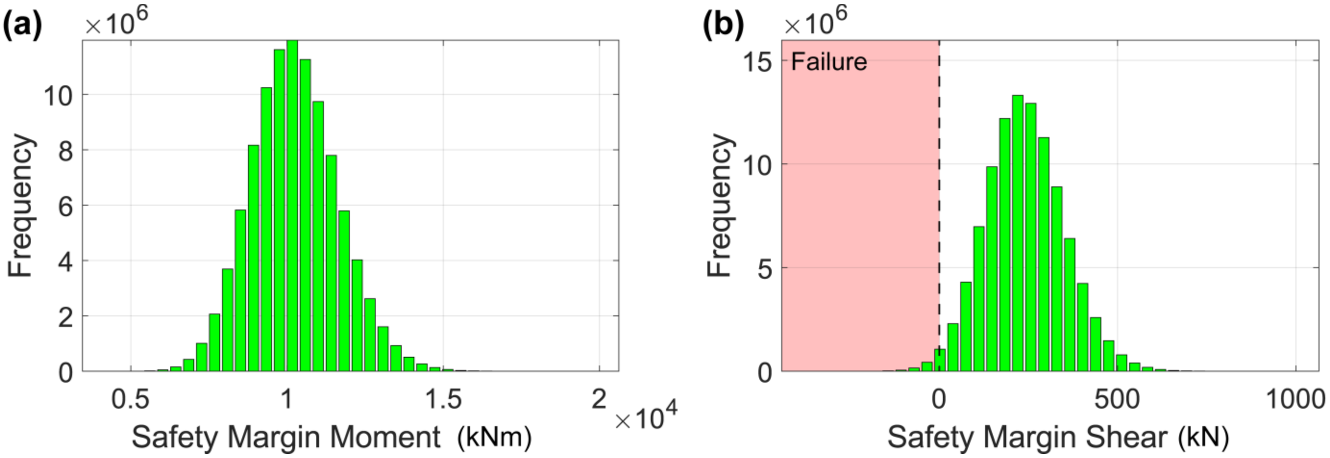

Figure 7: Safety margin histograms for (a) ductile and (b) brittle failure mechanisms at the cover spalling time.

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