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RELIABILITY OF GIRDER BRIDGE SYSTEM UNDER LATERAL UNEVEN VEHICULAR OVERLOADS

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Abstract. Truck presence on bridges is random. Trucks may centrically or eccentrically appear on a bridge span in one or more lanes, which will cause extra load effects on girder components and eventually influence structural performance. Especially when trucks are heavily loaded, their eccentric passage is possible to induce damage in components, and, thus, the prescribed load-delivery path will be changed among components within the system. Therefore, component- and system-level structural performance of bridges subjected to aggressive vehicular overloads need to be thoroughly addressed. In this study, a WIM-based 5-axle overloaded truck model is chosen, and it is gradually applied to the finite element models of two girder bridges with different eccentric distance, considering two loading scenarios of single truck and multiple trucks. In detail, trucks are transversely loaded with an incremental eccentric distance, to investigate the impacts of eccentric loadings on structural performance, including failure sequences of components, load distribution factors among components, as well as system redundancy, as structures entering nonlinear

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stage. Finally, the reliability indices of the two bridges under uneven overloads are assessed at the component level and system level, respectively. The results of this study were beneficial to structural evaluation bridges subjected to overloads to ensure their serviceability and integrity.

Keywords: eccentric passage, load distribution factor, nonlinear analysis, system redundancy and reliability, vehicular overloads.

Introduction

As critical components connecting communities for transportation, bridge structures have a profound effect on people's lives and further the entire society. During the past years, the safety and performance assessment of bridges have received a great amount of attention (Casas et al., 2013; Mehta et al., 2015; Ali et al., 2021; Tan et al., 2021). In recent years, with the growing transportation demand, bridges tend to subject to a variety of unfavourable stressors, such as heavy traffic volume and/or heavily loaded trucks, carrying indivisible industrial freight weighing several times more than the normal truck weight (Han et al., 2017). Therefore, Eurocode (CEN, 2003) has provided various basic models of special vehicles for abnormal loads that can be authorised to travel on particular routes of the European highway network. Moreover, truck presence is random, they may centrically or eccentrically appear on a bridge span in one or more lanes, which will cause a significant threat to structural performance and even structural safety (Fu et al., 2013; Zhou et al., 2020). Some disastrous accidents of collapse of bridges have happened (Zhou et al., 2014; Cao et al., 2021). These destructive events witnessed the aggressive impact of vehicular heavy loads on bridge safety, and also brought challenges and requirements to performance assessment of existing bridges. Note that structures are usually designed based on performance of components, then the system is regarded as safe acquiescently. However, system reliability is more complicate, especially when encountering some extreme events, like passage of vehicular heavy loads, may lead to damage in components. Consequently, the prescribed load-delivery path will be changed among components within the system, in this case, component- and system-level reliability both need to be further addressed, by synthesising material, components and system performance accordingly.

Reliability-based structural analysis has been widely used in bridge design and evaluation as a fundamental method, taking uncertainties in geometric dimensions, material properties, live loads, among others into account (Kang et al., 2011; Liao et al., 2017; Miao & Ghosn, 2016). Current bridge design specifications are also developed based on reliability theory, and a series of rational reliability indices is recommended for main components (Ministry of Transport of the People's Republic of China, 2020; AASHTO, 2007; 2010). However, this component-reliability-based approach has some limitations. For instance, the amount of live loads distributed to a girder component is calculated using a deterministic parameter, the so-called load distribution factor (LDF) prescribed in design specifications or manuals, assuming structures are linear elastic. It should be noted that LDF is actually a random variable with some statistical characteristics (Yan et al., 2016), and load redistribution among different girders will happen if structures enter plastic stage under some extreme loads, but the associated randomness and variety are usually ignored. In this regard, understanding the random characteristics of LDFs by nondeterministic methods is of vital important to investigate structural reliability in nonlinear stage, at both the component level and system level.

Previous studies related to vehicular heavy loads mainly focused on truck configurations, truck models, truck weight regulations and structural responses (Agostinacchio et al., 2014; Paeglitis & Paeglitis, 2014; Skokandic et al., 2019) and so on, in which, centric overload cases are mainly concerned (Fu & Hag-Elsafi, 2000; Grimson et al., 2008; Zhao et al., 2017; Han et al., 2018). Therefore, the impact of transverse eccentric heavy loads on structural safety and reliability is still an open area for further research. Although Han et al. (2019) discussed the passage of lateral eccentric customised transport vehicle on multigirder bridges, a majority of overloaded trucks on highway bridges still need to be concerned.

This paper mainly focuses on the influences of lateral uneven vehicular on bridge responses, nonlinear structural behaviours and safety of bridges in plastic stage, at the component and system levels. Firstly, a 5-axle overloaded truck model is established based on long-term recorded truck data, with statistics of axle load and axle spacing etc. Secondly, this model is gradually applied to the finite element models of pre-stressed concrete T-girder and box-girder bridges, respectively, in which, two loading scenarios of single truck and multiple trucks are considered. The trucks are transversely loaded with an incremental eccentric distance of 0.1 m to investigate the impact of eccentric loadings on failure sequences of components with the bridge system, as well as the load distribution factors among components when structures enter a nonlinear stage. Finally, the reliability indices of bridges under uneven overloads are assessed at the component level and system level, respectively.

1. Overloaded truck model

Kinds of standard traffic load models are available in various bridge design specifications or manuals (Ministry of Transport of the People's Republic of China, 2015; AASHTO, 2010; CEN, 2003). However, previous studies have reported these standard load models are generally inaccurate for representing operational live loads, especially for those overloaded trucks that greatly exceed the design values (Yu and Cai, 2019). Therefore, overloaded truck model based on real traffic data is indispensable for bridge safety and reliability analysis. Based on some previous works by authors, the severest effect-based method was proposed for filtering trucks with a high load level, potentially producing damage on bridges. Specifically, if a WIM truck's load effects exceed the values induced by the standard traffic load model specified in the bridge design code (Ministry of Transport of the People's Republic of China, 2015), then it can be regarded as an overloaded truck. In our previous work, all truck models were developed based on statistic parameters of overloaded trucks filtered, including a number of axles, gross vehicle weight (GVW), axle load and spacing of axles, etc. Since 5-axle trucks account for 80% of all filtered heavy trucks, the 5-axle truck model is applied to the investigated bridges in this study, considering different lateral eccentric distance away from the centre line, to investigate the failure probability of girder components and further the entire bridge system. Figure 1 shows the configuration of the 5-axle truck model. For

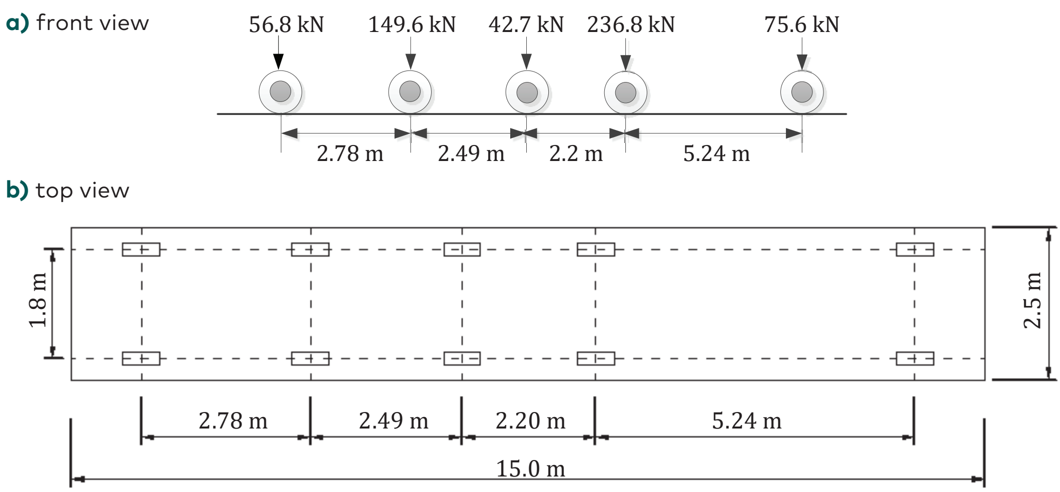

Figure 1. Configuration of the 5-axle truck

more details about the process of establishing this truck model, and the statistics of axle loads and axle spacing, the reader is referred to the original paper (Liu et al., 2019).

2. Finite element models

2.1. Simply supported T-girder bridge

Medium and small-span girder bridge makes a majority of infrastructures in China. The widely used T-girder bridge is selected from bridge design manual as a standard precast and pre-stressed concrete structure. This simply supported bridge has a span length of 20 m, consisting of five T-girders. It is designed to carry two-lane unidirectional traffic, so the bridge deck is 11.25 m wide and the girder is 1.5 m high with a uniform lateral distance of 2.25 m. The cross section of the superstructure is displayed in Figure 2(a).

2.2. Simply supported box-girder bridge

Another widely used bridge type in design manual is also concerned herein, as aforementioned, it was constructed and designed to carry two-lane traffic. The precast and pre-stressed box-girder bridge has a span length of 20 m, composed of three box-girders with 1.2 m height and 3.3 m lateral spacing, so the deck width is 9.9 m. The cross section of the superstructure is displayed in Figure 2(b).

The two finite element models are established in ANSYS platform, for both, 3D solid65 element is used to model decks, girders, and diaphragms to investigate their nonlinear structural behaviours under uneven overloaded trucks. Moreover, Link8 element is used to simulate

a) T-girder bridge **b)** Box-girder bridge

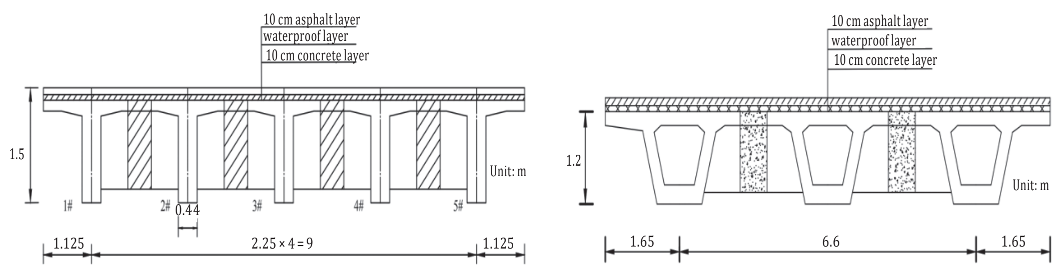

Figure 2. The cross sections of prototype bridges

(a) T-girder bridge **(b)** Box-girder bridge

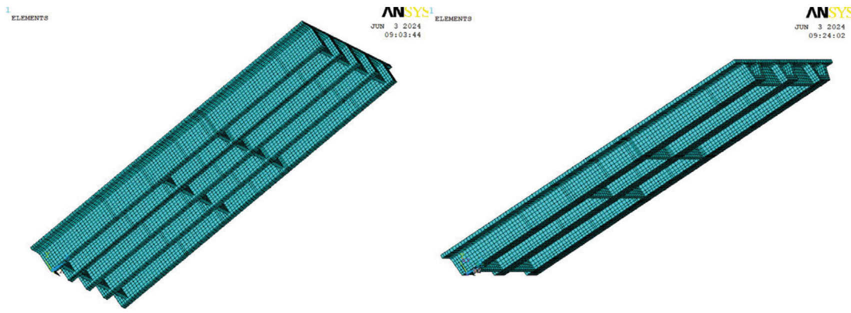

Figure 3. Finite element models

pre-stressed steels and they are tied to concrete by the same nodes; for regular steels, they are dispersed into concrete. Since the structural reliability is to be analysed based on nonlinear finite element theory, multilinear isotropic hardening model MISO and bilinear isotropic hardening model BISO are used for concrete and steel materials, respectively, and the Willam–Warnker five-parameter failure criterion is also used. The developed finite element models are shown in Figure 3.

3. Nonlinear structural behaviours under lateral uneven overloads

3.1. Single uneven vehicular overloaded model

The presence of trucks on bridges is random. They may centrically or eccentrically travel along the centre line of decks, since multiple lanes are usually available. Therefore, the FE models were adopted to compute the load effect of bridges under eccentrically overloaded trucks at the system level. To account for structural ductility and redundancy, material nonlinearity is considered in the FE models, for which, the nonlinear constitutive relationships of concrete, reinforcement bar and pre-stressed tendons are incorporated. In the first loading scenario, the 5-axle overloaded truck model is singly and gradually applied to the FE model. Specifically, axle loads of the truck proportionally increase, and the longitudinal position of the truck is determined using an influence line analysis, to find out the severest scenario for the flexural moment in the mid-span (Miao & Chan, 2002). To investigate the eccentric loading effect on girder components, the eccentric distance *e* is defined as the transverse distance between the centre line of the truck and the centre line of the deck, while the initial *e* equals zero. Then, a lateral increment of 0.1 m is taken; the sectional strain, stress and internal force are recorded for each loading step, until the most vulnerable girder fails (ductile failure), corresponding to yielding of steel and of rebar within the critical section of any girder. As the structure enters nonlinear state, flexural failure of the bridge system is reached. Note that the minimum clearances between the extreme-exterior wheels and the barrier edges are set as 1.0 m; thus, the maximum eccentric distances are 3.4 m and 2.6 m for T-girder bridge and box-girder bridge, respectively. The schematic loading scenarios are shown in Figure 4.

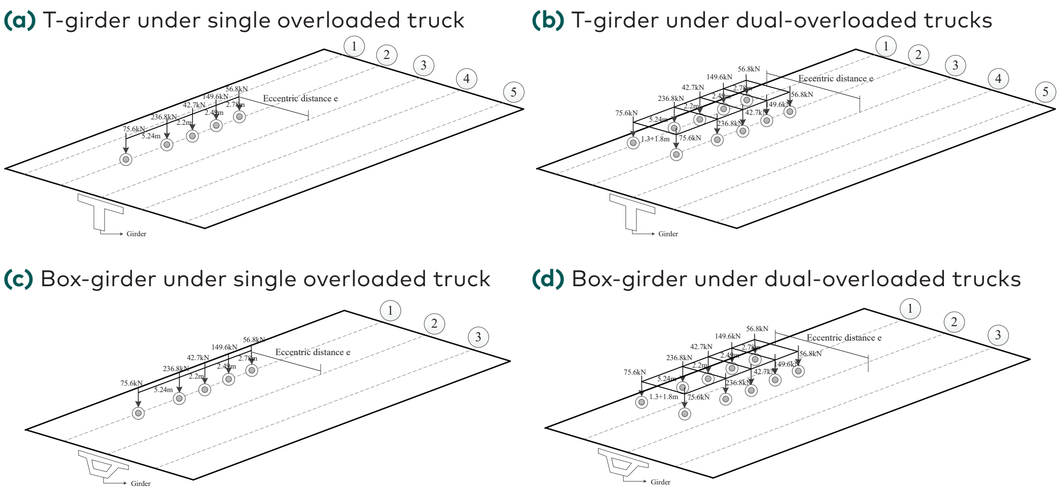

Figure 4. Schematic loading scenarios

3.2. Failure sequence of multiple girders under single overloaded truck

Since the predefined limit states of the bridge system are associated with flexure failure, the nonlinear moment-curvature relationship is firstly investigated. In this regard, the overloaded model is gradually applied to the bridge until the predefined limit states are reached. Specifically, the GVW of the truck is proportionally increased, while the distribution factors of per axle are kept constant, for which, the amplification factor of GVW is 4.5 in these cases, when the structural nonlinear stage is eventually reached. The *M*-*φ* curves of four typical loading cases of the T-girder bridge are displayed in Figure 5. As seen, the failure sequence is highly dependent on the eccentric distance. When the variable *e* falls into the range of 2.8~3.4 m, the most vulnerable girder is 1#, as numbered in Figure 4. When the *e* decreases into 1.2~2.8 m and 0~1.2 m, the most vulnerable girder becomes 2# and 3#, respectively. As two wheels load at the centre of two adjacent girders, the two girders are likely to yield simultaneously.

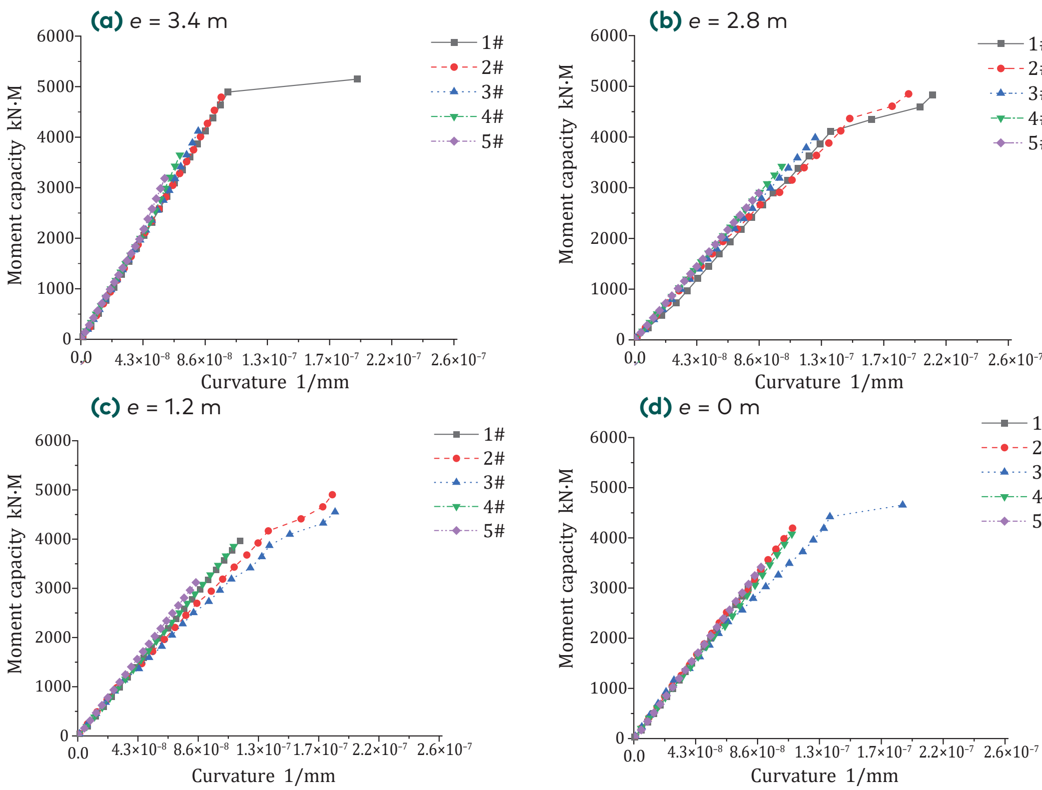

Figure 5. *M*-φ curves of T-girder under single overloaded truck

For the box-girder bridge, a similar phenomenon can be seen in Figure 6. When the eccentric distance falls into 1.6~2.6 m, i.e., the cases of the overloaded truck laterally move on 1# girder, resulting in its yielding at first. While *e* varies between 0 to 1.6 m, 2# girder is prone to fail. Also, 2# and 3# girders tend to yield simultaneously when the overloaded truck centrically presents on them. Note that the amplification factor of GVW becomes 5.7 for this bridge, and the curvature significantly increases when the moment capacity reaches about 5000 kN·m, which corresponds to the yielding of steel within the section of the most vulnerable girder, indicating box girders present better ductile performance than T girders, with great deformation capacity after the occurrence of yielding.

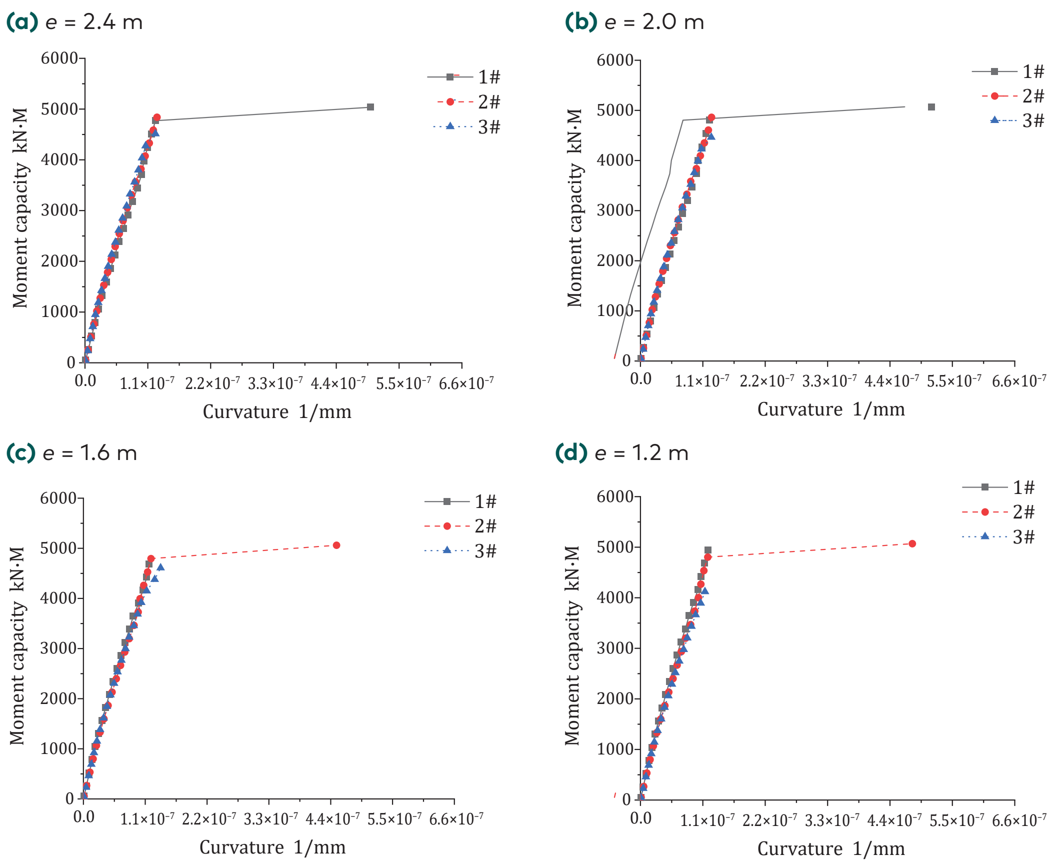

Figure 6. *M*-φ curves of box-girder under single overloaded truck

3.3. Multiple uneven vehicular overloaded model

Heavy trucks may appear on a highway bridge span in one or more lanes simultaneously. Trucks in multiple lanes can induce much higher load effects to bridge components than those in one lane (Fu et al., 2013). Therefore, the load effects and failure patterns of bridge system under multiple overloaded trucks need to be addressed. Note that the minimum clearance between the two trucks is 1.3 m, as specified in the Chinese *General Specifications for Design of Highway Bridges and Culverts* (Ministry of Transport of the People's Republic of China, 2015), also taking into account the deck width and minimum clearances between the exterior wheels and the barrier edges. Three clearances of 1.3, 1.5 and 1.7 m are set for the two 5-axle overloaded trucks loading on the T-girder bridge. The eccentric distance e is defined as the distance between the centre line of the bridge deck and that of the dual-truck system, consequently, the maximum e is 2.7 m, 1.7 m and 1.7 m for the three truck clearances, respectively. As before, the dual-truck system laterally moves with an incremental of 0.1 m.

The critical sectional M-φ curves with two typical eccentric distances of 1.7 m and 0.6 m are displayed in Figure 7, where the amplification factor of dual-truck weight is 1.6. As seen, truck clearance has negligible effect on failure patterns of the bridge system, when the e is the same, the most vulnerable girder is identical no matter how the truck clearance changes. Whereas e increases from 0.6 m to 1.7 m, the ductile performance of girders is quite different; the girder prone to yielding changes from 3# to 2#, and the ultimate carrying capacity, corresponding to crushing of concrete at the top fibre, i.e., the sectional failure of the most vulnerable girder, increases from 4500 kN·m to 5000 kN·m. Comparing with eccentric loading cases of single truck, the failure pattern of the bridge system under two trucks obviously changes. For one thing, the exterior girder that is apt to be the weakest one in the former cases turns to be elastic, whereas the interior girders would fail at first; for another thing, yielding of two girders at the same time would rarely happen, which occurs only for the truck clearance of 1.3 m, with eccentric distance larger than 1.0 m. Moreover, the ultimate carrying capacity does not significantly decrease in the two-truck loading cases, whereas the ductile performance of girders becomes worse, since the structure turns to fail after yielding soon, indicating degrading deformation capacity and presenting relative brittle failure pattern.

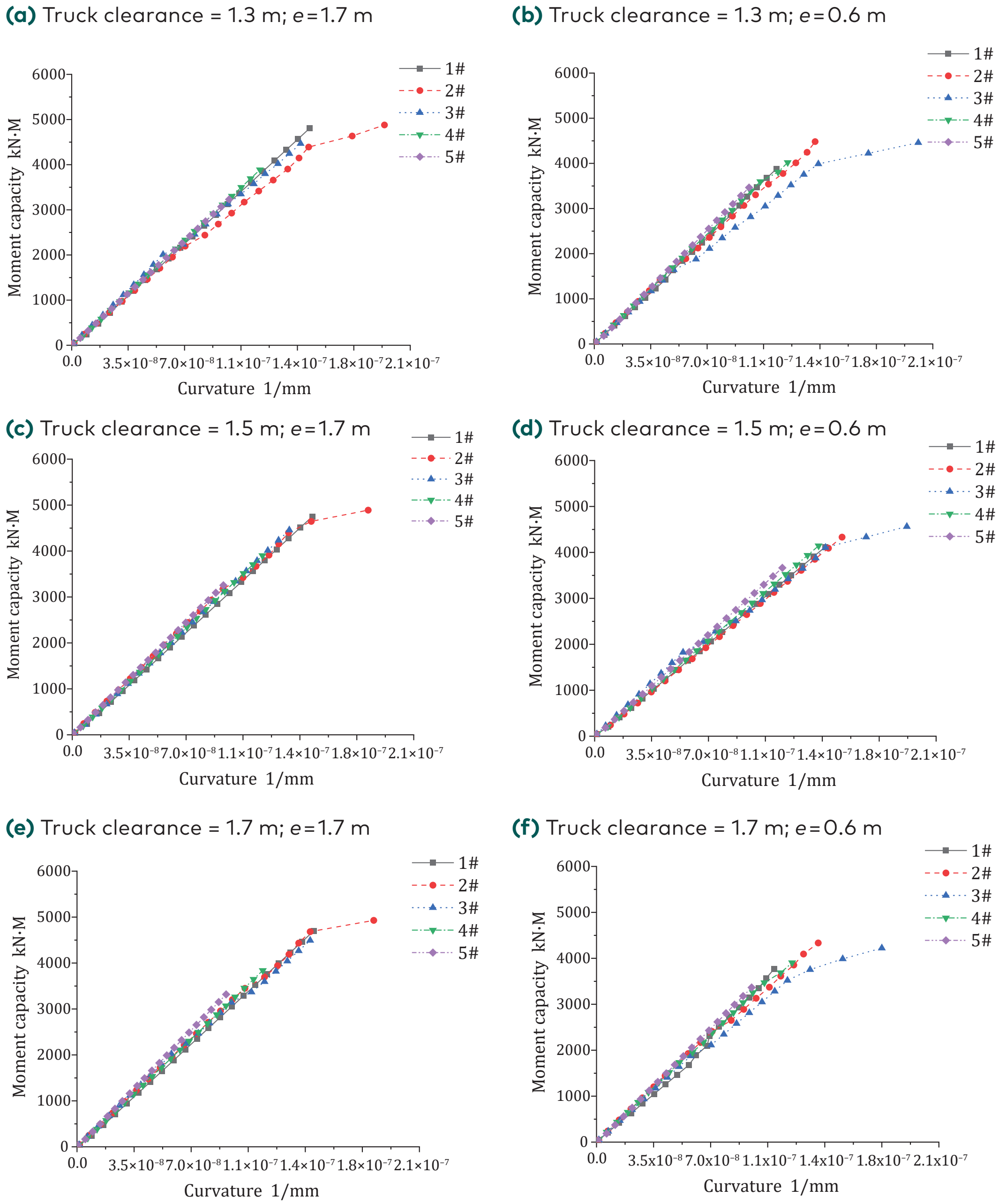

Figure 7. *M*-φ curves of T-girder under dual-overloaded trucks

As the worst loading scenario, the dual-truck system with the clearance of 1.3 m is also applied to the box-girder bridge, with a weight amplification factor of 1.4, to investigate its nonlinear structural behaviour. The same eccentric incremental is used, and the maximum *e* equals 1.2 m due to a narrower deck width. The sectional *M*-*φ* curves are shown in Figure 8. It can be seen, at certain eccentric positions, the yielding of two girders also occurs, and similar with single vehicular loading cases, box girder presents good ductile performance with a remarkable increase of curvature after yielding at about 5000 kN·m. Differentiating from the T-girder bridge, the exterior box-girder is prone to yield when the eccentric distance *e* is relatively large; this may be related to the wider transverse spacing between box girders. As a result, the exterior girder is close to the dual-truck loading system.

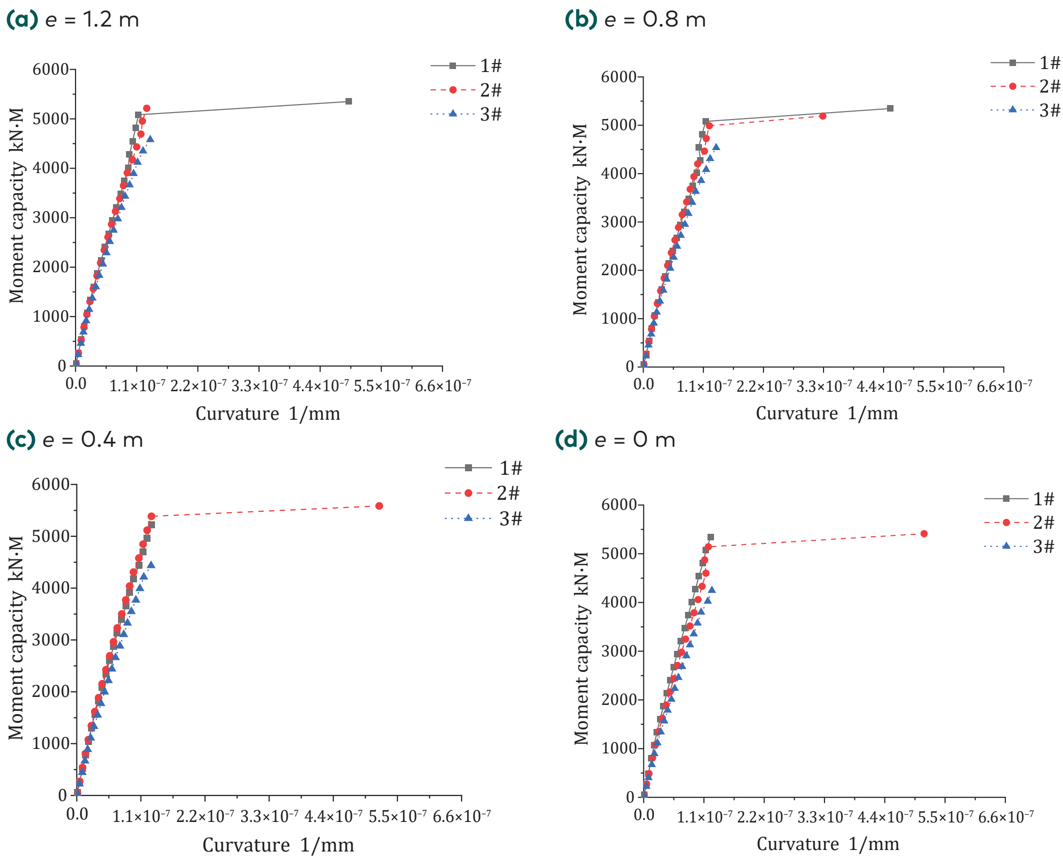

Figure 8. *M*-φ curves of box-girder under dual-overloaded truck

3.4. Bridge system redundancy analysis

Redundancy is a critical indicator within the performance assessment of structural systems, presenting a quantitative relationship between component and system safety (Ghosn et al., 2010; Zhu et al., 2012; Fiorillo & Ghosn, 2022). Conceptually, for a structure system, when encountering failure of the weakest component or even several components, component ductility could increase the possibility and extent of force redistribution among the remaining components and then contribute to system redundancy. Therefore, redundancy of a structural system is usually assessed by combing the overall structural performance and its components, and it is generally defined as the capability of a structure to continue to carry loads after the ductile failure of the most critical component (Frangopoal & Curley, 1987).

It can often be observed that the most vulnerable girder fails first, whereas the bridge system can still sustain the applied loads until the ultimate limit state is approached. With respect to the investigated multi-girder RC bridge systems, to be conservative, ductile failure is defined as the first occurrence of yielding under uneven overloads, and the system limit state as flexural failure of any girder within the bridge system.

By the nonlinear structural performance curves (i.e., the M-φ curves) of the bridge systems obtained in the previous sections, given the sectional curvature φ, the failure moment M_{u} at system limit state, and the first yielding moment M_{y}, can be obtained. The ratio between the two can be used to quantify the system redundancy, and it is expressed as follows (Ghosn & Moses, 1998):

$$R = \frac{M_{\mathrm{u}}}{M_{\mathrm{y}}}. \tag{1}$$

The calculated system redundancies with various eccentric distances are listed in Tables 1 and 2, for the T-girder bridge and box-girder systems, respectively. The concerned eccentric distances are in line with the previous analyses. It can be seen that system redundancies are generally small under various eccentric loading conditions, indicating weak structural ductile capacity after the first occurrence of yielding. Besides, eccentric distance has little influence on bridge system redundancy, which demonstrates the relationship between structural flexural failure and structural yielding.

Table 1. System redundancy of the T-girder bridge under various eccentric loading conditions

Single truck		Dual-truck system			
			truck clearance = 1.3 m	truck clearance = 1.5 m	truck clearance = 1.7 m
e	redundancy	*e*	redundancy	redundancy	redundancy
3.4	1.053	1.7	1.111	1.111	1.111
2.8	1.181	1.4	1.111	1.111	1.133
1.2	1.267	0.9	1.111	1.111	1.111
0	1.053	0.6	1.059	1.053	1.059

Table 2. System redundancy of the box-girder bridge under various eccentric loading conditions

Single truck		Dual-truck system (truck clearance = 1.3 m)	
e	redundancy	*e*	redundancy
2.4	1.056	1.2	1.053
2.0	1.045	0.8	1.047
1.6	1.055	0.4	1.037
1.2	1.056	0	1.053

4. Lateral load distribution factors under uneven vehicular overloads

The live load distribution factor is a very important parameter in both bridge design and evaluation. Previous studies have shown that there can be large discrepancy between the actual distribution factors of field bridges and the theoretical ones specified in bridge design codes. Since the load distribution factor is a random variable with certain statistical properties (Kim & Nowak, 1997), it is generally treated as a constant. In fact, the amount of live load distributed to a particular girder depends on many factors, such as the loading position of trucks, the load-distributing characteristics of the bridge and diaphragm elements, etc. (Chung et al., 2006; Harris, 2010). Among them, the transverse loading position of trucks has a remarkable effect on the LDFs of bridges in operation, especially for uneven overloading scenario, the distributed live load on each component tends to be different and highly dependent on the eccentric distance. Thus, adopting reasonable LDFs is of vital important for checking load-carrying capacity of components. Moreover, the occurrence of yielding of any girder within a bridge system will lead to redistribution of live loads among all girders. Therefore, the characteristics of LDFs for nonlinear structural system need to be addressed to understand the path of live loads being delivered.

There are several theoretical methods for LDF calculation, among them, the eccentric compression method is commonly used in bridge design manuals. Specifically, the standard truck model specified in the bridge design code (Ministry of Transport of the People's Republic of China, 2015) is placed along transverse direction with deterministic distance; structures are assumed to be linear elastic, and the influence line is used. This method is easy to implement, but whether it can be applied to nonlinear structural analysis needs to be validated. In this regard, the LDF calculated by the eccentric compression method (i.e., Chinese specification method) is referred to as "theoretical LDF" below. Comparatively, the real LDF is defined as the ratio of the load effect of each girder to the bridge system. To be consistent, the load effect is specified as the bending moment at the mid-span induced by each lateral loading step discussed in the previous sections. Then, the real LDF can be expressed as follows:

$$\mathrm{LDF} = \frac{M_i}{\sum_{i=1}^{n} M_i}, \tag{2}$$

where M_i denotes the moment at the mid-span of the i-th girder under each loading case; n is the number of girders.

The theoretical LDFs (denotes as η) are listed in Table 3. They are normalised by the summation of the factors, as shown in braces. The normalised LDFs for each girder under single overloaded truck with different eccentric distances are displayed in Figure 9 as a function of e.

Table 3. Theoretical LDFs and their normalised values

Girder	1#	2#	3#	4#	5#
η	0.79(0.25)	0.60(0.19)	0.40(0.13)	0.60(0.19)	0.79(0.25)

It can be found that the computed LDFs significantly vary with the eccentric distance, namely, the transverse loading position of overloaded trucks. Since the truck model is loaded from the centre line of the deck and laterally move at the right side, the LDFs of girders far away from the truck are smaller and generally decrease with e, whereas those close to truck wheels increase and are larger than the theoretical counterparts. It should be noted that LDF is not constant for any components, and the

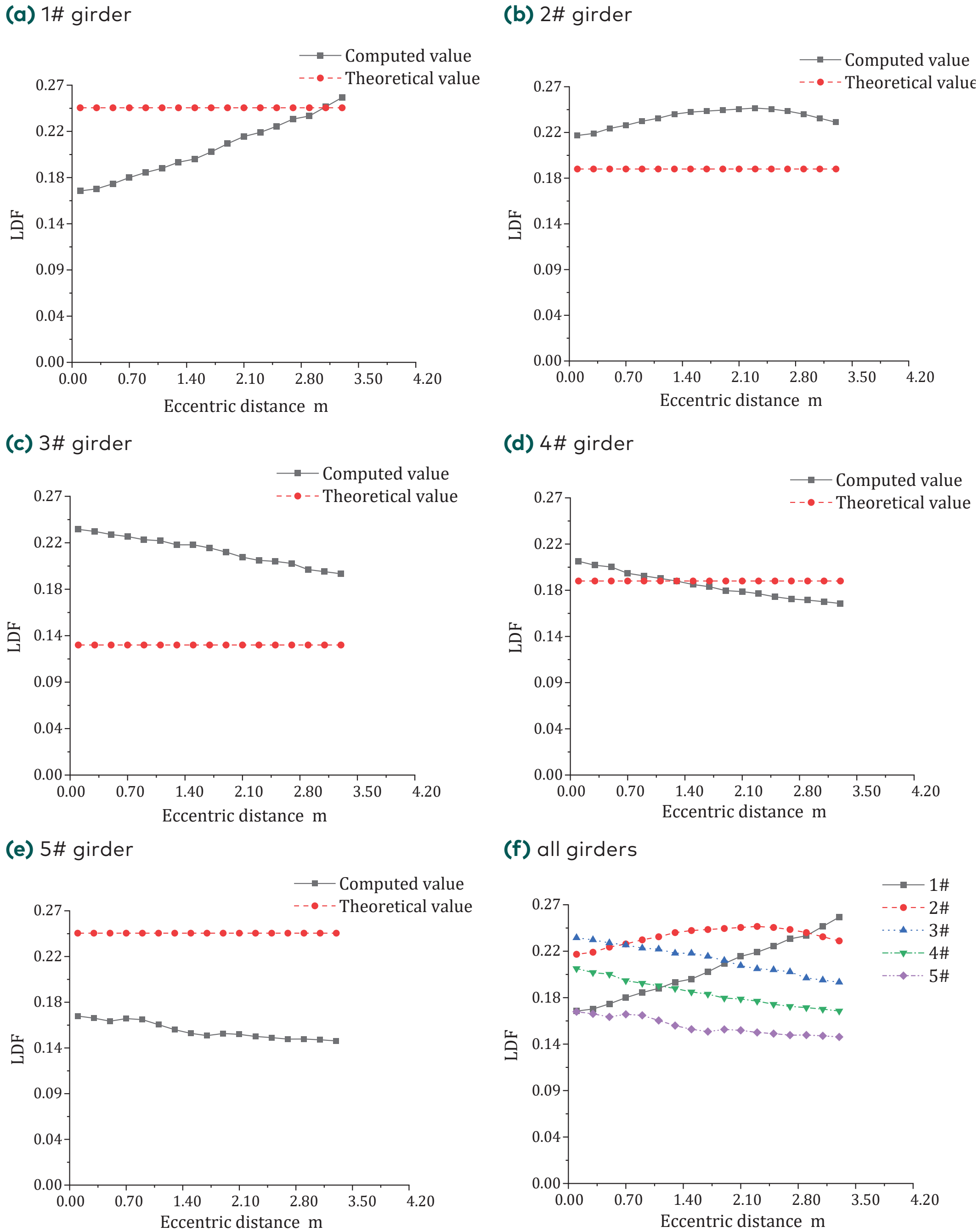

Figure 9. Comparison of the computed LDFs with the theoretical LDFs (single truck)

live loads expected to be sustained by each component are different, even when the truck is placed on the centre line (i.e., e = 0). The LDFs are not symmetrically distributed, not as assumed in the theoretical method. It can be concluded that unevenly distributed overloads will remarkably change the live loads assigned to each component, and, consequently, component reliability varies.

Similarly, the LDFs of girders under multiple uneven overloaded trucks, i.e., the dual-truck system, are also calculated and plotted in Figure 10. As seen, the LDFs of exterior girders are always smaller than their theoretical counterparts, whereas interior girders are larger. Note that LDFs of 3# girder are nearly two times the theoretical ones, indicating underestimated live loads are assigned to this component, which may correspond to some very unsafe loading scenarios. In general, the truck clearance has negligible effect on LDFs.

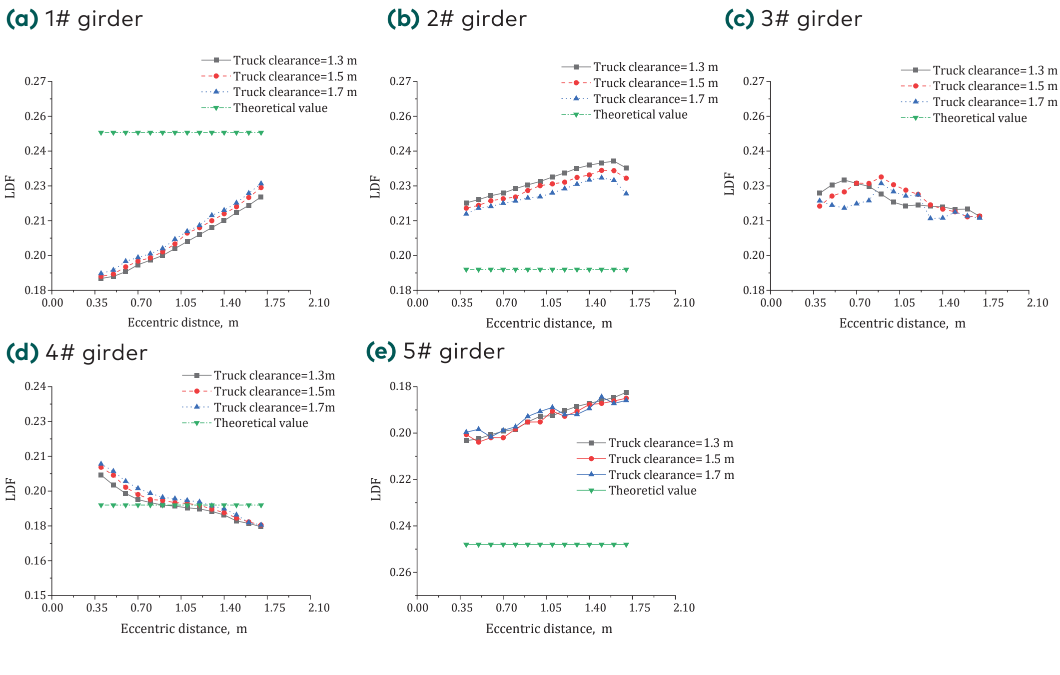

Figure 10. Comparison of LDFs in this study with a provisional value (dual-truck)

5. Reliability of bridge system under uneven overloads

5.1. Resistance and live load effect

The structural resistance is first evaluated using the FE model in a probabilistic manner. Given the associated random variables of materials and geometric dimensions, the bridge model is implemented with ANSYS to capture the system resistance. Since the system limit state is pre-defined as the flexural failure of any girder within the bridge system, the resistance of girder is first represented as the critical sectional resistance to bending moment, when the ultimate state of yielding of normal steel bars and the crushing of concrete at the top edge is reached. Note that at this stage, the pre-stressed tendons are tensile but have not yielded, whose contributions to the ultimate load carrying capacity need to be considered. The strain compatibility method is used to obtain strengths of the pre-stressed tendons, based on the sectional linear relationship between the ultimate compression strains of concrete at the top and the tension strains of concrete near the pre-stressed tendons. By 5000 times random simulations of the associated variables, whose statistic parameters are given in Table 4, the calculated mean and standard deviation of the bending resistance of the T-girder are 5586.38 and 26.78 kN·m, respectively. On the other hand, the dead load is applied to the FEM and then combined with the load effect induced by the overloaded truck model, considering lateral uneven loading scenarios (both single truck and dual-truck system). At each eccentric loading step, the flexural moment at the mid-span of each girder is extracted to calculate statistics, as an illustration, the statistics of dead load effects and live load effects under single overloaded truck with e up to 3.3 m, are listed in Table 5. For other loading case, the same statistics are calculated.

Table 4. Statistics of random variables for bending resistance

Random variable	Mean	Std	CV
Girder height	1.0064	0.0257	0.0255
Girder width	1.0013	0.0081	0.0081
Rib thickness	1.0320	0.1052	0.1019
Concrete cover depth	1.0178	0.0505	0.0496
Concrete C50	1.3877	0.1907	0.1374
Steel	1.0849	0.0780	0.0719

Table 5. Statistic parameters of load effects under single truck (units: kN·m; *e* up to 3.3 m)

Load type	Statistics	1#	2#	3#	4#	5#
Dead load	Mean	1522.20	1522.20	1522.20	1522.20	1522.20
	Std	656.10	656.10	656.10	656.10	656.10
Live load	Mean	2488.94	2172.02	1650.94	1240.08	896.54
	Std	390.70	340.95	259.15	194.66	140.73

5.2. Reliability of component and system

The performance functions of a structure can be identified as follows:

$$Z = R - S, \tag{3}$$

where R and S denote structure resistance and load effect, respectively.

Since a bridge system consists of several components, and, thus, the system resistance, load effect and reliability are consequently dependent on its components. Probability models of resistance and load effect for components have been established in the previous sections, considering flexural failure of the critical section within a girder component. Given the limit state function above, the component reliability indices can be firstly computed using JC method (Rackwitz & Fiessler, 1978).

The relationship curves between the reliability index of each girder and the eccentric distance are plotted in Figure 11, to be a reference, the target reliability index for ductile failure recommended in the bridge design code (Ministry of Transport of the People's Republic of China, 2015) is also included. It is noticeable that the passage of vehicular overloads is somehow abnormal case in bridge safety assessment, and the corresponding considerations are not entirely covered by specifications. Moreover, structures entering nonlinear plastic stage are not considered in bridge design, and, thus, nonlinear properties of materials are neglected in structure resistance calculation. The limit state defined in this study is extended to plastic state. It can be observed that the reliability indices of those yielded girders are much smaller than the target reliability index, since the live loads are approximating their ultimate carrying capacity, except the reliability indices of 5# girder that never yielded. With the increase of eccentric distance, the reliability indices of girder 5 also increase, since the vehicular overloads are far away from it. This is opposite to girder 1, which is being approached contrarily, and for other girders, the indices fluctuate with eccentric distance, highly depending on the loading positions.

As discussed above, the system limit state is defined as the flexural failure of any girder, and the multiple T-girder bridge system is treated

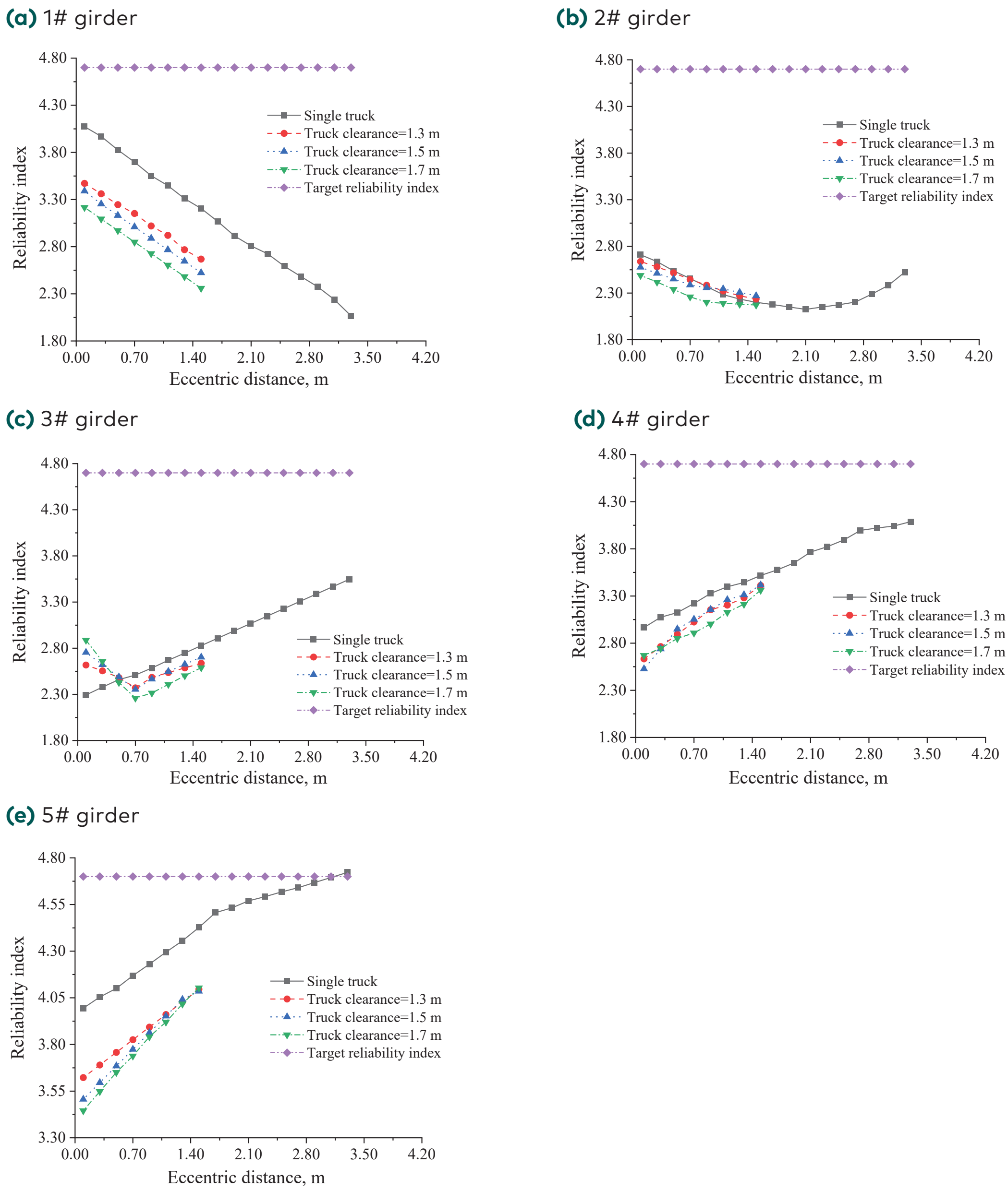

Figure 11. The relationship of structural reliability index and eccentric distance

as a serial system, then the failure probability of the system can be calculated. The failure probability versus the eccentric distance is shown in Figure 12. It can be seen, the failure probability sharply fluctuates with *e*; the maximum failure probability happens at *e* = 0.7 m under the dual-truck system with a truck clearance of 1.7 m. The second maximum failure probability happens at *e* = 3.3 m under the single truck, indicating that the transverse loading positions would considerably affect structural safety rather than GVW. The most unfavourable loading scenario generally occurs when truck wheels get close to the girders, while it becomes more reliable when wheels locate at the cast-in-site joints between two adjacent girders.

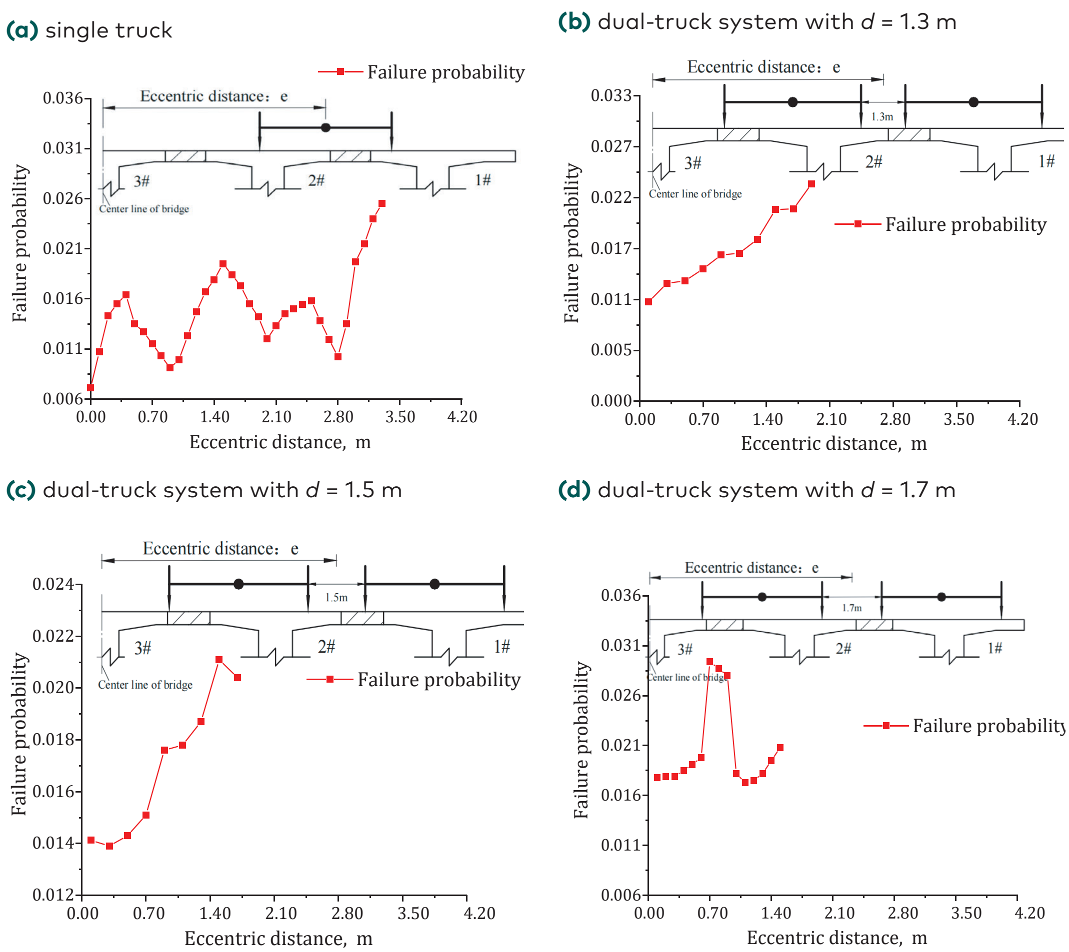

Figure 12. Failure probability versus eccentric distance

Conclusion

In this paper, a typical 5-axle overloaded truck model was established based on long-term recorded truck data. By applying this truck model, structure responses and nonlinear structural behaviours of RC multigirder bridges were investigated at the component level and system level, respectively, to understand the impact of eccentric vehicular overloads on bridge safety. The following conclusions can be obtained from this study:

1. According to the nonlinear analysis for bridges under the ultimate state defined in this study, the failure sequences of components are highly dependent on the eccentric distance; as two wheels loading on the centre of two adjacent girders, the two girders are likely to yield simultaneously. Comparatively, the box girders present better ductile performance than the T girders, with great deformation capacity after the occurrence of yielding.
2. It was found that LDFs significantly varied with the eccentric distance, namely, the transverse loading position of overloaded trucks. It should be noted that the LDF is not constant for any component and the live loads expected to be sustained by each component are different. Even when the truck is placed on the centre line, the LDFs are not symmetrically distributed, not as assumed in the theoretical method. Unevenly distributed overloads would remarkably change the live loads assigned to each component, and, consequently, structural reliability varies.
3. Structures entering nonlinear plastic stage are not recommended in bridge design for better serviceability and safety, and, thus, nonlinear properties of materials are generally reserved in structure resistance calculation. The limit state defined and investigated in this study directly extends to plastic state. It can be observed that the reliability indices of those yielded girders are much smaller than the target reliability index recommended in the bridge design specification, since the live loads are approximating the ultimate carrying capacity of girders.
4. For the failure probability of the bridge system, it sharply fluctuates with e. The maximum failure probability happens at e = 0.7 m under the dual-truck system, and the second maximum failure probability happens at e = 3.3 m under single truck, indicating that the transverse loading positions would considerably affect structural safety rather than gross vehicle weight. The most unfavourable loading scenario generally occurs when truck wheels get close to the girders, while it becomes more reliable when wheels locate at the cast-in-site joints between two adjacent girders.

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DATA AVAILABILITY STATEMENT

Some or all data, models, or code that support the findings of this study are available from the corresponding author upon reasonable request.

DISCLOSURE STATEMENT

Authors are required to include a statement at the end of their article to declare whether or not they have any competing financial, professional, or personal interests from other parties.

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