THE CALCULATION OF CHARACTERISTIC DYNAMIC EFFECTS OF TRAFFIC LOADING ON BRIDGES

Colin C. Caprani[1]*, Arturo González[2], Paraic H. Rattigan[3], and Eugene J. OBrien[4]

ABSTRACT

The determination of bridge lifetime load effect is a complex problem. Usually, statistical extrapolation of simulated static load effect is used to derive a lifetime characteristic static load effect. In reality, when a vehicle crosses a bridge, dynamic interaction occurs which often causes a greater total load effect. This total load effect is related to the static load effect through a dynamic amplification factor (DAF). Often the worst estimated DAF is applied to the lifetime static load effect to obtain a total lifetime characteristic load effect. This does not allow for the reduced probabilities of both high static loading and high dynamic interaction. The authors present an approach that accounts for this reduced probability by using multivariate extreme value theory, in conjunction with extensive static simulations and 3-D finite element bridge-truck dynamic interaction models. It is found that the DAF that should be applied to the characteristic static load effect is significantly less than originally thought. This has significant implications for the type of traffic (free-flowing or congested) thought to govern short- to medium-length bridges.

CE DATABASE SUBJECT HEADINGS

Bridge loads, Statistics, Dynamic loads, Probabilistic models, Traffic, Simulation, Finite Element Method, Interaction models.

AUTHORS' BYLINES

* Corresponding author.

[1] Post-doctoral researcher; School of Architecture, Landscape and Civil Engineering, University College Dublin, Earlsfort Terrace, Dublin 2, Ireland. Tel.: +353-1-716-7367; Fax: +353-1-716-7399; E-mail: colin.caprani@ucd.ie

[2] Lecturer; School of Architecture, Landscape and Civil Engineering, University College Dublin, Earlsfort Terrace, Dublin 2, Ireland. E-mail: arturo.gonzalez@ucd.ie

[3] Doctoral researcher; School of Architecture, Landscape and Civil Engineering, University College Dublin, Earlsfort Terrace, Dublin 2, Ireland. E-mail: paraic.rattigan@ucd.ie

[4] Professor of Civil Engineering; School of Architecture, Landscape and Civil Engineering, University College Dublin, Earlsfort Terrace, Dublin 2, Ireland. E-mail: eugene.obrien@ucd.ie

1. INTRODUCTION

Often in engineering it is not the outcome of a single stochastic process that is of interest, but the combination of several processes. It is well known that truck crossing events cause the truck and bridge to interact dynamically. With such interaction there is an associated dynamic component to the total loading that results. This total load effect is usually greater than the static load effect.

For static traffic loading, many authors have described methods of calculating characteristic values and a detailed review is given by Caprani (2005). While other approaches may be possible, most authors to date have fitted maximum load effects to the family of Extreme Value statistical distributions and have extrapolated to determine the characteristic value.

From studies that separate the dynamic and static loads induced by loading events (Fryba 1999, Brady at al 2005), the dynamic amplification factor (DAF) is defined as:

$$\varphi = \frac{\varepsilon_T}{\varepsilon_S} \qquad (1)$$

where ε represents the load effect under consideration, and the subscripts denote the static (S) load effect and total (T) value of the load effect, which includes any dynamic interaction.

The Eurocode (EC1.3 1994) traffic load model has been developed from the simulation of static traffic actions (Bruls et al 1996). The dynamic amplification factors of Figure 1(b) are applied to the 1000-year characteristic static load effects and are included in the load model of Figure 1(a).

As the worst static and dynamic cases are combined, such loading is conservative because it does not recognize the reduced probability of two extremes (static and dynamic aspects) occurring simultaneously.

The bridge-truck(s) interaction is sufficiently complex that the dynamic aspect of the load effect may be considered as a random variable. Therefore, with any given crossing event, there are two resulting processes: static and total load effect. For the assessment of bridges, it is critical combinations of these two processes that are of interest.

Multivariate extreme value theory is the statistical tool that is used to analyse critical combinations of several processes. Such an approach includes the respective probabilities of occurrence as well as any relationship between the variables. This theory is used here to incorporate the dynamic interaction of the bridge and trucks into an extreme value analysis for total load effect. The results of this analysis are used to determine a dynamic allowance factor that may be applied to the results of static simulations to determine an appropriate lifetime total load effect. The analysis is performed for a notional site, derived from two well-studied data sources.

2. BRIDGE AND TRAFFIC BASIS OF MODEL

The Bridge

The Mura River bridge in Slovenia is used as the basis of the method proposed in this paper. This is a two-lane, bi-directional, 32 m simply-supported bridge span which forms part of a multi-span structure. It consists of 5 longitudinal pre-stressed concrete beams, a reinforced concrete slab, and 5 transverse diaphragm beams. A 3-dimensional finite element model was developed (Brady et al 2006, Brady and OBrien 2006) in which dynamic behaviour of the model was calibrated against measured responses for single and two-truck meeting events.

The general arrangement of the Mura River Bridge is shown in Figure 2. The finite element model was used to determine the influence lines for each of the longitudinal girders. These influence lines, as well as polynomial fits to them, are shown in Figure 3. The polynomial fits are required as input to the simulation program. It can be seen that the asymmetry of the beams is reflected in the influence lines and that the polynomial fits are mostly indistinguishable from the finite element influence lines.

The Traffic

One week of Weigh-In-Motion (WIM) data was taken from the A6 motorway near Auxerre, France. The site has 4 lanes of traffic (2 in each direction) but only the traffic recorded in the slow lanes was used and it is acknowledged that this results in conservative loading. In total 17 756 and 18 617 trucks were measured in the north and south slow lanes respectively, giving an average daily truck flow of 6744 trucks. The recorded WIM data was analysed (Grave 2001) for the statistical distributions of the traffic characteristics of the site for each lane as follows:

Gross Vehicle Weight:

Modelled as tri-modal Normal distribution – described below;

Axle spacings:

Modelled as uni- or bi-modal Normal distributions, as appropriate to the data;

Axle weights for 2- and 3-axle trucks:

Modelled as tri- or bi-modal Normal distributions, as appropriate to the data;

Axle weights for 4- and 5-axle trucks:

Axle weight expressed as a percentage of Gross Vehicle Weight (GVW) for the first and second axles and for the remaining tandem group. In each case, the percentage is modelled as a Normal distribution

Composition:

The measured percentage of 2-, 3-, 4- and 5-axle trucks is used;

Speed:

Modelled as a Normal distribution and considered independent of truck type and uncorrelated with GVW;

Flow rates:

For each hour of the day, the average flow rate (ignoring weekend days) was used for all the days available;

Headway:

This is modelled with a number of distributions dependent on flow, as described in OBrien & Caprani (2005).

More information on the modelling of traffic characteristics can be found in Caprani (2005), Grave (2001), and OBrien and Caprani (2005).

3. SIMULATIONS

Static Simulations

Monte Carlo simulation is used to generate 10 years of bi-directional, free-flowing traffic data and this traffic is passed over the influence line for Beam 1 to determine the load effects that result. Each year of simulation is broken into 'months' of 25 working days each and there are thus 10 such months in each year of simulation (allowing for weekends and national holidays). As a basis for further analysis, the events corresponding to monthly-maximum static load effect are retained. This is done to minimize the number of events that are to be dynamically analysed, as well as providing a shorter 'extrapolation distance'.

Of the 100 monthly-maximum events, 20 are found to be 1-truck events, 77 to be 2-truck events and 3 are 3-truck events. The influence surface for Beam 1 is asymmetrical; therefore trucks in Lane 1 dominate, reducing the effect of trucks in Lane 2. Hence the monthly-maximum events are derived from the occurrence of heavy trucks in Lane 1, and trucks with less extreme GVW in Lane 2. Figure 4 illustrates some examples of the monthly-maximum events; the prevalence of heavy trucks in Lane 1 (top lane) is evident.

Dynamic Simulations

The 100 monthly-maximum loading events obtained from the simulations are analysed using the finite element bridge-truck interaction models developed by González (2001) and Rattigan et al (2005). The finite element bridge model used for the simulations is based on an experimentally validated model developed by Brady et al (2006) using 2-axle and 3-axle rigid vehicle models.

The finite element truck models were modelled using rigid bodies supported by suspension and tyre systems. The trailer and tractor masses in the trucks are modelled as point loads distributed throughout the frame by rigid elements. The suspensions and tyres are modelled as spring dashpot systems. The mechanical characteristics (suspension and tyre properties) of the rigid 2-axle and 3-axle configuration truck models are based on parameters given by Baumgärtner (1998) and Lutzenberger and Baumgärtner (1999). The mechanical properties of the articulated truck models are based on values proposed by Kirkegaard et al (1997), and are kept constant throughout. Figure 5 illustrates a sample 5-axle articulated truck model and shows the bridge model.

The end result of these bridge-truck interaction simulations is a population of 100 monthly-extreme loading events for which both total and static load effects are known. It is acknowledged that only the static load effects are maximum-per-month and it is possible that other events that are below the maximum statically could result in a greater total load effect. It is also acknowledged that variations in truck mechanical properties will influence the total load effect.

4. STATISTICAL INVESTIGATION OF RESULTS

Preliminary Results

A scatter plot of the total and static load effect values is shown in Figure 6(a). There is a relationship between static and total load effect – as may be expected as static constitutes the greater part of the total load effect. Each point on this graph represents the bivariate data corresponding to a particular load effect. Scatter plots of DAF against total and static load effect are given in Figure 6(b) and (c) and it can be seen that a positive correlation exists between total load effect an DAF, and little correlation exists between static load effect and DAF.

Multivariate extreme value analysis

It is usual in multivariate extreme value analyses to adopt the componentwise maxima approach (Coles 2001, Demarta 2002), that is, the maximum static effect, and the maximum total effect. In the present application this means that monthly maximum total and static load effects should have been noted independently of each other and their comprising loading events. However, it is not believed that there is much error introduced by using the monthly maximum static load effects and the associated total load effect value for the particular loading event.

Multivariate distribution modelling can be divided into two separate parts: modelling the marginal distributions and modelling the dependences through a copula (Demarta 2002). In this way, appropriate marginal and dependence structures can be developed separately and then combined (Embrechts et al 2003). When multivariate data is analysed to find extremes, the copula representing the dependence structure also becomes extreme (Segers 2004) and Pickands

(1981) provides a general class of extreme-value copula. Tawn (1988) describes the use of this copula for the bivariate extreme value case.

Based on Pickands' general extreme value copula, Stephenson (2005) discusses eight different forms of bivariate extreme value distributions that have emerged in the literature. Of these, the Gumbel bivariate extreme value distribution has been found to model the dependencies between total and static load effect well:

$$G_{Gu}\left(x,y\right)=\exp\left\{-\left(z_1^{1/\alpha}+z_2^{1/\alpha}\right)^{\alpha}\right\} \tag{2}$$

where $0<\alpha<1$ and is similar a dependence measure. Independence is represented by $\alpha=1$ and complete dependence occurs when $\alpha\to 0$. Capéraà et al (1997) describe the fitting of the Pickands' dependence function upon which this work is based.

Bivariate Extreme Value Analysis of Load Effect Data

In the analysis that follows, software developed by Stephenson (2005) is used in conjunction with bespoke algorithms, written in the *R* language for statistical computing (*R* Development Core Team 2005). Stephenson's (2003) method for simulating multivariate extreme value random variables is also used.

The data is fitted using the Gumbel logistic bivariate extreme value distribution, given in equation (2). The results of the fit can be seen in Figure 7: subplot (a) shows a contour plot of the bivariate probability density function and subplot (b) illustrates the empirical and fitted dependence structure of the data. It can be seen that the dependence function is modelled quite well - this is the determining factor in the choice of the Gumbel bivariate extreme value distribution for this work. The parameters of the Bivariate Extreme Value Distribution (BEVD) model are given in Table 1.

Bootstrapping for lifetime load effects

To estimate the distribution of lifetime load effect a parametric bootstrapping approach is used (Davison and Hinkley 1997). The 100-year lifetime of the bridge is simulated in each bootstrap replication. To do this, 1000 synthetic monthly-maximum events (100 years with 10 'months' per year) are simulated from the fitted BEVD model (any inaccuracy of the BEVD fit to the data is not taken into account in this procedure). The component-wise maxima are recorded and these values are not related through an individual loading event. The maximum total and static load effects from the 1000 bootstrap replications of the bridge lifetime are noted; these points are given in Figure 8.

The ratio of static lifetime load effect to total lifetime load effect is termed here as the Bridge Lifetime Dynamic Ratio (BLDR). This recognizes that the same event is not necessarily responsible for the maximum lifetime total and maximum lifetime static load effects. It can be seen from Figure 8(b) that there is a strong negative linear correlation between BLDR and static effect. This is significant: it means that the dynamic ratio is falling as more extreme load effects are considered.

Assessment Dynamic Ratio

A Gumbel bivariate extreme value distribution is fitted to the simulated lifetime maxima. The results are shown in Figure 9 and the parameters given in Table 2. The bridge lifetime load effects and parent distribution are equally scaled and plotted in Figure 10. It is clear that there is dependence between the static and total maximum-in-lifetime load effect values – even though they are not related through individual loading events, and this must be a result of the dependence in the parent distributions.

The characteristic static load effect value is commonly found using Monte Carlo simulation and some form of statistical analysis (Caprani 2005). It is a value that links the characteristic total load effect to the characteristic static load effect that is of interest, not the distribution of BLDRs. The term characteristic is defined in EC 1.3 (1994) as being that value which is expected to be exceeded with a probability of 10% in 100 years. Therefore, the 10% quantile of the lifetime BEVD marginal distributions are appropriate. The appropriate BLDR is termed an Assessment Dynamic Ratio (ADR) and is defined as:

$$\varphi_q = \frac{G_T^{-1}(q)}{G_S^{-1}(q)} \tag{3}$$

where q is the quantile of interest of the marginal distributions $G_T(\cdot)$ and $G_S(\cdot)$. Therefore, for Eurocode design, $q = 0.9$ for a 100-year design life. This value is appropriate to relate lifetime static to total load effect values, and is shown in Figure 9. This ADR has a value of 1.0575.

By applying the stability postulate (Coles 2001) to the marginal distributions, plots of ADR against various other design lives by quantile can be derived and are shown in Figure 11; some values are given in Table 3. It is clear that as the design life or quantile increase, the ADR reduces. Caprani (2005) re-parameterizes the ADR and derives a numerical distribution of ADR concluding that the return period at which no dynamic allowance is required is of the order 2.6×10^{6} years. Therefore, it can be concluded that some dynamic allowance will always be required for usual design lives.

5. SUMMARY

In this paper, the current means of allowing for dynamic interaction of bridge and truck(s) is reviewed and shown to be conservative. Simulations of static load effect are used to obtain monthly maximum loading events, which are then modelled dynamically to obtain the total load effect: that which results from the dynamic interaction of the bridge and trucks. It is shown that there is significant statistical correlation between the two variables, and dependence models are described that allow for this.

Bivariate extreme value analysis is used to model the monthly maximum total and static load effects, and allow for their inter-dependence. Parametric bootstrapping is used to generate 100-year extremes from the fitted bivariate distribution. In this manner, a distribution of bridge lifetime dynamic ratio is derived. It is again shown to be bivariate, with a similar dependence structure to the monthly maximum events, even though the variables are no longer related through a single event.

It is shown that the dynamic allowance reduces with increasing load effect and that, for the bridge and traffic studied, the design dynamic allowance required for the characteristic load effect is 5.8%. It is also shown that this allowance decreases slowly with increasing safety level. Whilst the dynamic allowance results presented here are specific to this bridge and traffic, the method presented is general. These findings have significant implications for the modelling and assessment of existing bridges. If further evidence shows that dynamic allowances can be as low as 6% at the lifetime load effect level, free-flowing traffic can no longer be considered as the governing case for short-to-medium length bridges (Bruls et al 1996). Traffic jam scenarios would then need to be studied extensively for short- to medium-length bridges and research into the dynamics of bridge-truck interaction for such bridges would be affected.

NOTATION

The following symbols are used in this paper:

$G_S(\cdot)$	=	Generalized Extreme Value distribution function of static load effect;
$G_T(\cdot)$	=	Generalized Extreme Value distribution function of total load effect;
$G_{Gu}(x,y)$	=	Gumbel bivariate extreme value distribution function;
q	=	a quantile of a distribution;
z_1, z_2	=	transformed marginal distribution variables given by Tawn (1988);
α	=	dependence parameter of the Gumbel bivariate extreme value distribution;
α_{Q1}, α_{Q2}, α_{q1}, α_{q2}	=	nationally-determined modification factors for the Eurocode traffic load model;
ε_S	=	static load effect;
ε_T	=	total load effect;
φ	=	dynamic amplification factor;
φ_q	=	assessment dynamic ratio derived from the quantile q of the lifetime bivariate Gumbel extreme value distribution;
λ_U	=	tail dependence measure of Embrechts et al (2003);
μ	=	location parameter of the Generalized Extreme Value distribution;

σ	=	scale parameter of the Generalized Extreme Value distribution;
ξ	=	shape parameter of the Generalized Extreme Value distribution.

REFERENCES

Baumgärtner, W. (1998), *Bridge-Truck Interaction: Simulation, Measurements and Load Identification,* 5th International Symposium on Heavy Vehicle Weights and Dimensions, Maroochydore, Australia, 1998.

Brady, S.P., OBrien, E.J., Znidaric, A. (2006), 'The Effect of Vehicle Velocity on the Dynamic Amplification of a Vehicle crossing a Simply Supported Bridge', *Journal of Bridge Engineering*, ASCE, 11(2), 241-249.

Brady, S.P. and OBrien, E.J. (2006), 'Effect of Vehicle Velocity on the Dynamic Amplification of Two Vehicles Crossing a Simply Supported Bridge', *Journal of Bridge Engineering*, ASCE, 11(2), 250-256.

Bruls, A., Calgaro, J.A., Mathieu, H. and Prat, M. (1996), 'ENV1991 – Part 3: The main models of traffic loads on bridges; background studies', *Proceedings of IABSE Colloquim*, Delft, The Netherlands, IABSE-AIPC-IVBH, 215-228.

Capéraà, P., Fougres, A.L., and Genest, C. (1997), 'A nonparametric estimation procedure for bivariate extreme value copulas', *Biometrika*, 84, 567-577.

Caprani, C.C. (2005), *Probabilistic Analysis of Highway Bridge Traffic Loading*, Ph.D. Thesis, School of Architecture, Landscape, and Civil Engineering, University College Dublin, Ireland.

Coles, S.G. (2001), *An Introduction to Statistical Modeling of Extreme Values*, Springer-Verlag, London.

Davison, A.C. and Hinkley, D.V. (1997), *Bootstrap Methods and Their Application*, Cambridge University Press, Cambridge.

Demarta, S. (2002), *Multivariate Extreme Value Theory and Copulas*, Diploma Thesis, ETH Zentrum, Switzerland, <http://www.math.ethz.ch/~demarta/diplom.pdf> (Mar. 15, 2006).

EC 1 (1994): *Basis of design and actions on structures, Part 3: Traffic loads on bridges*, European Prestandard ENV 1991-3: European Committee for Standardisation, TC 250, Brussels.

Embrechts, P., Lindskog, F. and McNeil, A. (2003), *Modelling Dependence with Copulas and Applications to Risk Management*, chapter in *Handbook of Heavy Tailed Distributions in Finance*, ed. S. Rachev, Elsevier, 329-384.

Fryba, L. (1999), *Vibration of Solids and Structures Under Moving Loads*, Telford, London.

Gonzalez, A. (2001), *Development of Accurate Methods of Weighing Trucks in Motion*, PhD Thesis, Department of Civil Engineering, Trinity College Dublin.

Grave, S.A.J. (2001), *Modelling of Site-Specific Traffic Loading on Short to Medium Span Bridges*, Ph.D. Thesis, Department of Civil Engineering, Trinity College Dublin.

Kirkegaard, P.H., Nielson, S.R.K., Enevoldson, I. (1997), *Heavy Vehicles on Minor Highway Bridges – Dynamic Modeling of Vehicles and Bridges*, Department of Building technology and Structural Engineering, Aalborg University, ISSN 1395-7953 R9721, December.

OBrien, E.J. and Caprani, C.C. (2005), 'Headway modelling for traffic load assessment of short- to medium-span bridges', *The Structural Engineer*, Vol. 83, No. 16, August, 33-36.

Lutzenberger, S. and Baumgärtner, W. (1999), *Interaction of an Instrumented Truck Crossing Belleville Bridge*, Proceedings of the Final Symposium of the project WAVE, Ed. B. Jacob, Hermes Science Publications, Paris, 239-240.

Pickands, J. (1981), 'Multivariate extreme value distributions', *Proceedings of the 43rd Session of the International Statistical Institute*, 49, 859–878.

Rattigan, P.H., Gonzâlez, A. OBrien, E.J., Brady, S.P. (2005), *Transverse variation of dynamic effects on beam-and-slab medium span bridges*, Proceedings of Eurodyn 2005, Ed. C. Soize, Paris, France, 1643-1648.

R Development Core Team (2005), *R: A language and environment for statistical computing*, R Foundation for Statistical Computing, Vienna, Austria, <http://www.r-project.org> (Mar. 15, 2006).

Segers, J.J.J. (2004), *Non-parametric inference for bivariate extreme-value copulas*, CentER Discussion Paper 2004-91, <http://center.uvt.nl/staff/segers/publications.html> (Mar. 15, 2006).

Stephenson, A.G. (2005), *A Users Guide to the* evd *Package (Version 2.1)*, May, <http://cran.r-project.org/> (Mar. 15, 2006).

Tawn, J.A. (1990), 'Modelling multivariate extreme value distributions', *Biometrika*, 77, 245-253.

TABLES

Table 1: Parameters of fitted monthly-maximum bivariate extreme value distribution.

Marginal Distributions					
Total Load Effect			Static Load Effect		
μ	σ	ξ	μ	σ	ξ
6.972	0.3851	0.2071	6.756	0.2423	0.1233
Dependence Measures					
BEVD dependence parameter			Tail dependence		
$\alpha = 0.5347$			$\lambda_U = 0.5514$		

Table 2: Parameters of 100-year lifetime fitted BEVD distribution.

Marginal Distributions					
Total Load Effect			Static Load Effect		
μ	σ	ξ	μ	σ	ξ
8.386	0.0950	0.2425	7.881	0.1079	0.1566
Dependence Measures					
BEV dependence parameter			Tail dependence		
$\alpha = 0.5513$			$\lambda_U = 0.5346$		

Table 3: Derived ADR values for sample design lives and quantiles.

Design Life (yrs)	**Quantile**	
	0.5	0.9
50	1.0649	1.0597
75	1.0639	1.0584
100	1.0631	1.0575
200	1.0612	1.0554
1000	1.0562	1.0505

FIGURE CAPTIONS

Figure 1: Eurocode Load Model: (a) Static Loading (the α factors reflect traffic on national networks or different classes of road); (b) Allowance for Dynamic Interaction (DAF – Dynamic Amplification Factor).

Figure 2: Mura River bridge, Slovenia: general arrangement.

Figure 3: Finite element influence lines for the Mura River bridge, Slovenia.

Figure 4: Examples of monthly-maximum events – GVW is noted on each truck in tonnes and Lane 1 is uppermost: (a) 1-truck; (b) 2-truck; (c) 3-truck.

Figure 5: Finite element models: (a) 5-axle truck; (b) bridge.

Figure 6: Scatter plots of maximum-per-month static and corresponding total load effect and DAF: (a) Maximum-per-month static and corresponding total load effect; (b) DAF against static load effect; (c) DAF against total load effect.

Figure 7: Results and diagnostic plots of the BEVD fit: (a) Bivariate distribution; (b) Dependency structure.

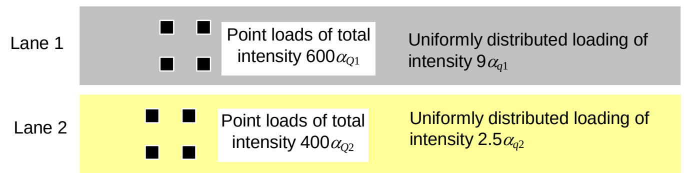
Figure 8: Scatter plots (showing linear regression lines) of Bridge Lifetime Dynamic Ratio: (a) Total load effect; (b) Static load effect.

Figure 9: Representation of the ADR for the Eurocode quantile.

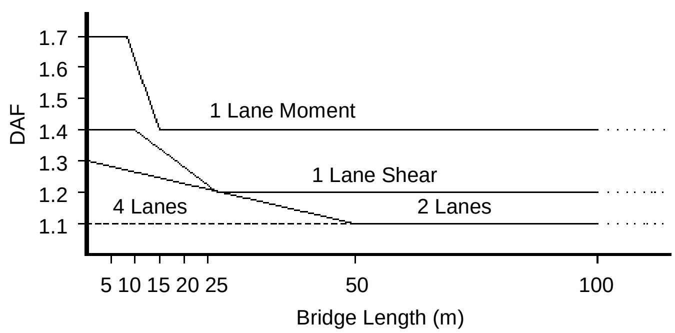
Figure 10: Maximum-per-month and lifetime bivariate distributions.

Figure 11: ADR quantile plots for various design lives, showing Eurocode calculation.

FIGURES



(a)



(b)

Figure 1

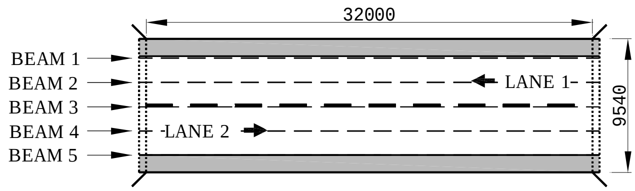


Figure 2

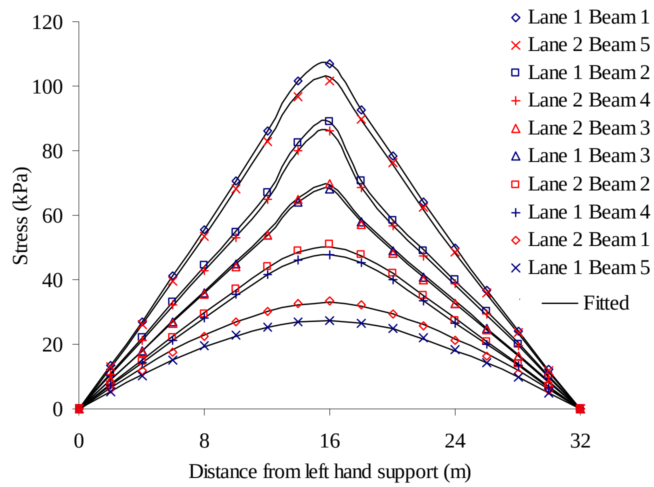
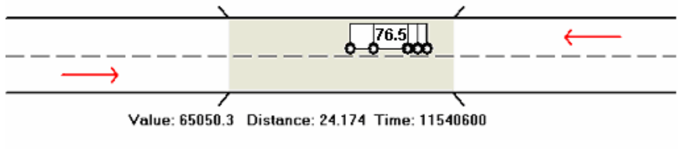
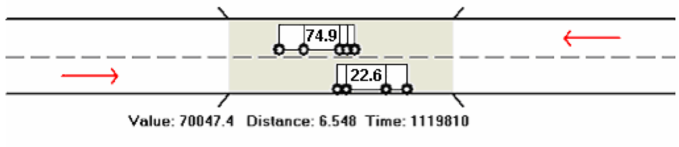

Stress (kPa)
120
100
80
60
40
20
0
0
8
16
24
32
Distance from left hand support (m)
Lane 1 Beam 1
Lane 2 Beam 5
Lane 1 Beam 2
Lane 2 Beam 4
Lane 2 Beam 3
Lane 1 Beam 3
Lane 2 Beam 2
Lane 1 Beam 4
Lane 2 Beam 1
Lane 1 Beam 5
Fitted

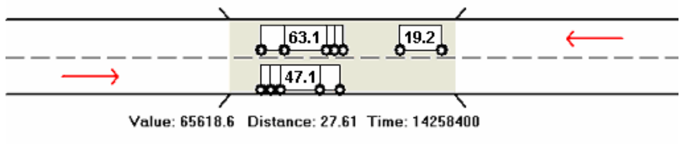
Figure 3


76.5
Value: 65050.3 Distance: 24.174 Time: 11540600

(a)

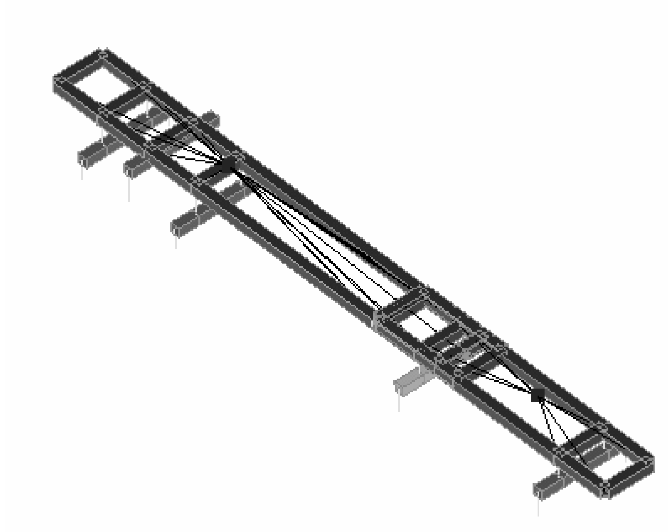

74.9
22.6
Value: 70047.4 Distance: 6.548 Time: 1119810

(b)

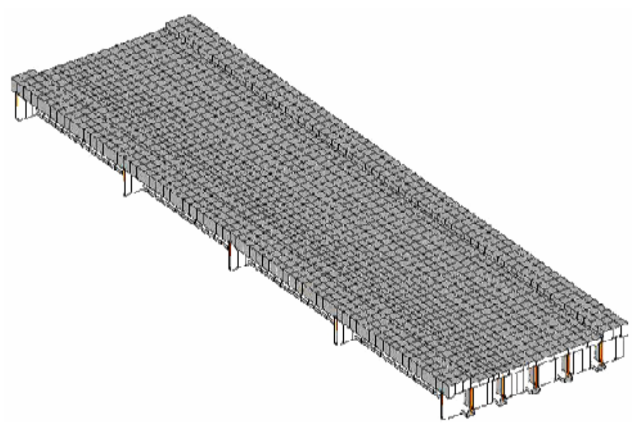

63.1
19.2
47.1
Value: 65618.6 Distance: 27.61 Time: 14258400

(c)

Figure 4

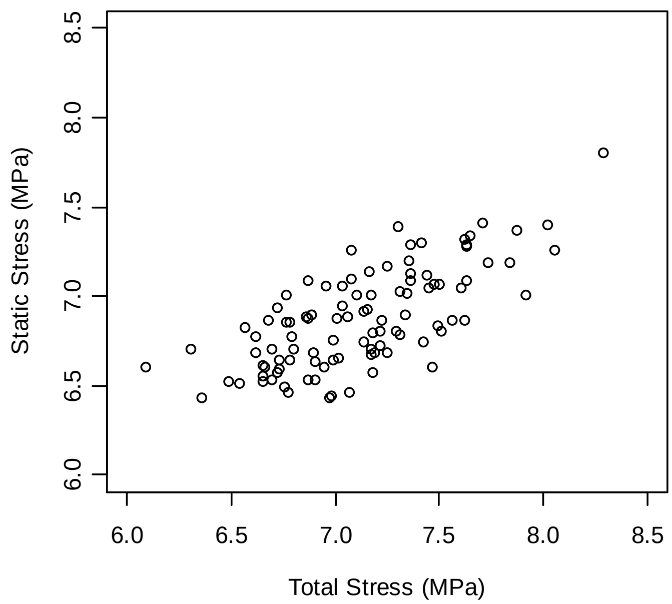


(a)

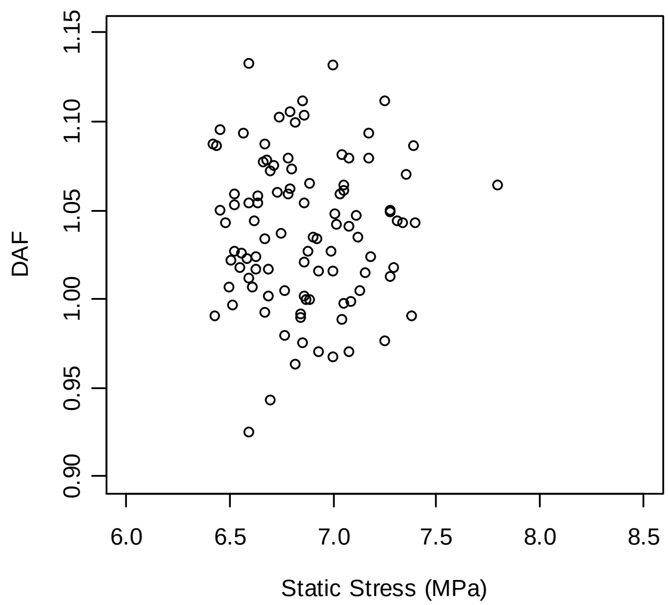


(b)

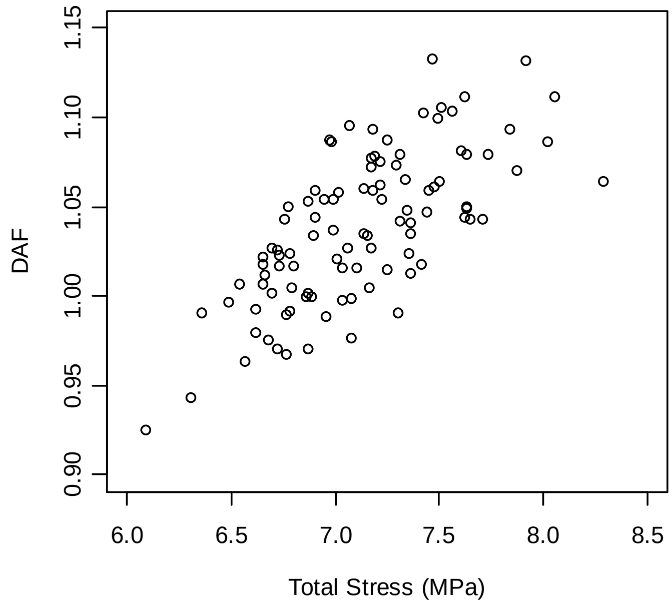
Figure 5


Static Stress (MPa)
6.0
6.5
7.0
7.5
8.0
8.5
Total Stress (MPa)

(a)

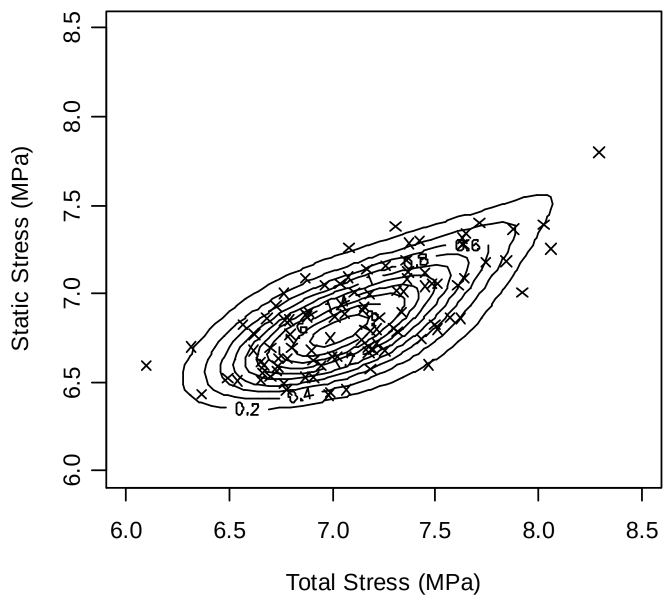

DAF
0.90
0.95
1.00
1.05
1.10
1.15
6.0
6.5
7.0
7.5
8.0
8.5
Static Stress (MPa)

(b)

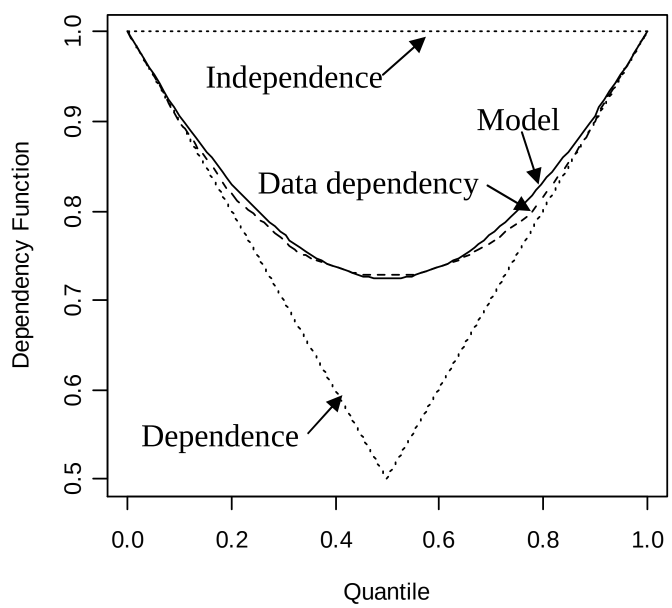


(c)

Figure 6

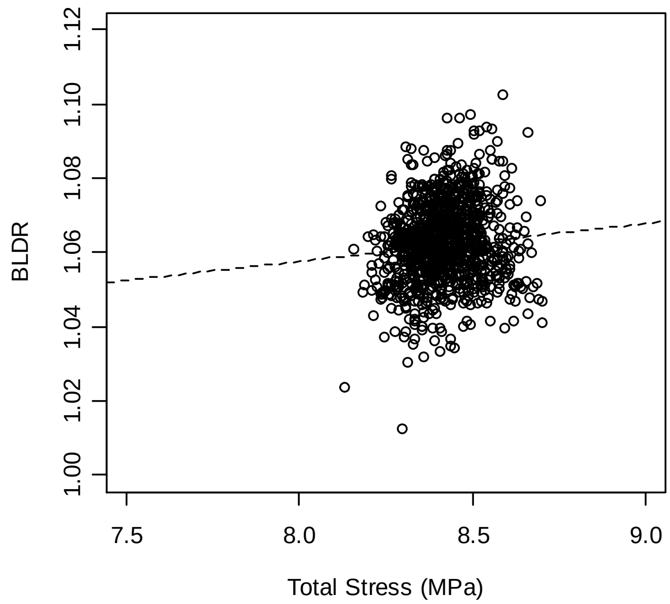

Static Stress (MPa)
Total Stress (MPa)
6.0
6.5
7.0
7.5
8.0
8.5
0.2
0.4
0.6

(a)

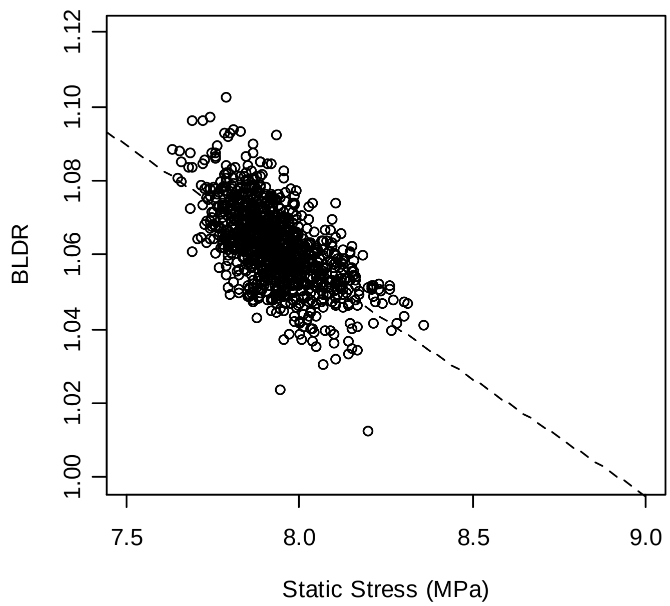

Dependency Function
Quantile
Independence
Model
Data dependency
Dependence
0.0
0.2
0.4
0.6
0.8
1.0
0.5
0.6
0.7
0.8
0.9

(b)

Figure 7


1.12
1.10
1.08
1.06
1.04
1.02
1.00
BLDR
7.5
8.0
8.5
9.0
Total Stress (MPa)

(a)


1.12
1.10
1.08
1.06
1.04
1.02
1.00
BLDR
7.5
8.0
8.5
9.0
Static Stress (MPa)

(b)

Figure 8

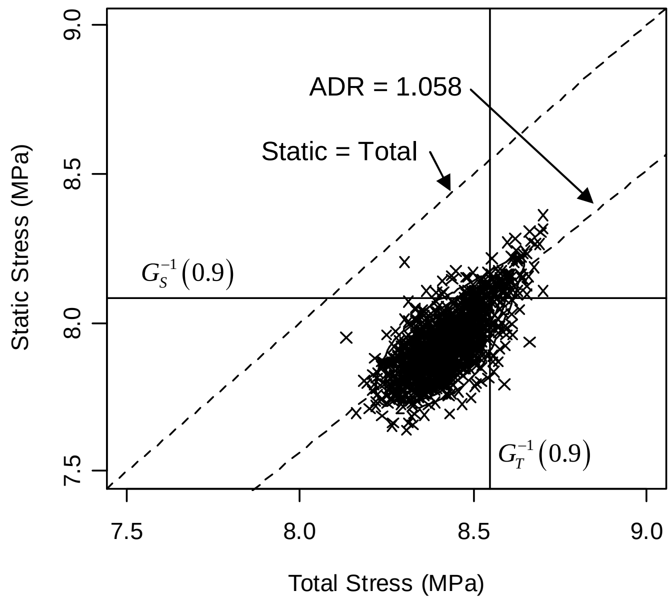

ADR = 1.058
Static = Total
$G_S^{-1}(0.9)$
$G_T^{-1}(0.9)$
9.0
8.5
8.0
7.5
Static Stress (MPa)
7.5
8.0
8.5
9.0
Total Stress (MPa)

Figure 9

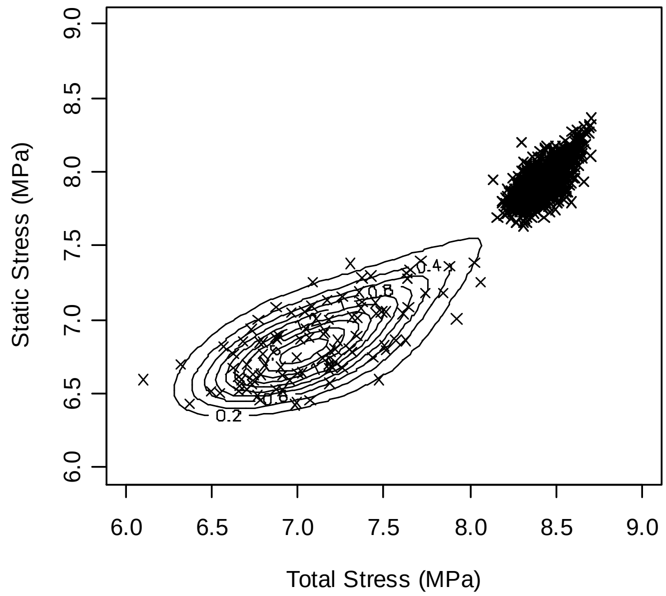

Static Stress (MPa)
Total Stress (MPa)
6.0
6.5
7.0
7.5
8.0
8.5
9.0
0.2
0.4
0.6
0.8

Figure 10

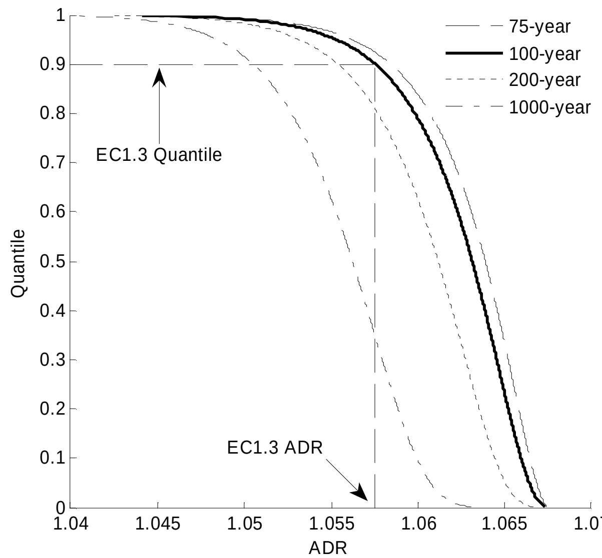

75-year
100-year
200-year
1000-year
EC1.3 Quantile
EC1.3 ADR
Quantile
ADR
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
1.04
1.045
1.05
1.055
1.06
1.065
1.07

Figure 11