Approximation of blast loading and single degree-of-freedom modelling parameters for long span girders

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Abstract

In this paper, the modelling of long-span girders under blast loads is presented. Specifically, spans in the range of 80–160 feet, on the order of those used for typical highway girder bridges, are considered. Topics addressed in this paper include (1) applicability of a uniform equivalent load to model blasts acting on long spans, (2) mathematical development of resistance functions and dynamic transformation factors for beams subjected to multiple distributed loads, and (3) comparisons of dynamic single degree-of-freedom analyses using both a work-equivalent uniform load and an approximation using three distributed loads of variable lengths relative to a detailed representation of the blast load profile as a function of position and time using finite element analyses. Analytical studies showing the sensitivity of the results to variations in the assumptions used to determine the magnitude and length of the loading pattern are provided. Based on these studies, a new method for approximating the response of long-span girders subjected to blasts with small scaled standoffs is proposed, which differs from the equivalent uniform load approach that is typically utilized. The new method is used to carry out parametric studies of bridge superstructure response predictions as part of research work performed for a state pool-funded bridge security project and an NCHRP project involving blast-resistant bridges.
Keywords: blast load, uniform equivalent load, distributed load, bridge girder, single degree-of-freedom, SDOF, load-mass factor, bridge loading, long span.

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1 Introduction

Determining the response of a structure or structural component to blast loading can be a challenging task due to the fact that blast loads vary with both time and position and structures respond dynamically, often with large deformations, in response to these loads. A wide range of analytical techniques, ranging from detailed, coupled multiple degree-of-freedom (MDOF) finite element models to simple single degree-of-freedom (SDOF) models, can be used to provide information about structural behaviour. Depending on the resources available and the required fidelity of the results, a decision must be made about the most suitable analysis technique. Through the use of a sound set of assumptions, SDOF models can be effectively utilized to capture important characteristics of structural response while using a minimal amount of computational resources and analyst time. For these reasons, SDOF modelling is commonly considered the state-of-practice for modelling responses of simple components subjected to blast loading.

This paper addresses a refinement of assumptions made about characteristics of loading for bridge girders modelled as SDOF systems. Refinement is necessary to improve the quality of the results obtained by these simple models. The methods presented and discussed herein are intended to be consistent with the level of complexity typically employed with SDOF models. It is recognized, however, that some increase in analysis setup time over simple uniform loadings may occur.

When analyzing a structural component subjected to blast loads, model parameters that characterize the system, including the applied dynamic loading, must be specified. A SDOF model attempts to approximate the distributed mass and stiffness of a system or component through the use of discrete properties that account for key response characteristics, such as the maximum deflection at a critical location (e.g., midspan of a girder under transverse uniform loading). Previous work by Biggs [2] and others provides detailed information on the modelling of beams and slabs using an SDOF representation. In order to equate the actual system to the SDOF system, certain work equivalency factors must be determined and applied to the SDOF mass and load. These load and mass factors are based on the distribution of the actual mass and actual load on the real structure relative to the simplified SDOF model. This paper discusses calculation of these parameters for loading that is more complex than the uniform distributed loading that is typically considered in blast-resistant design.

2 Applicability of uniform equivalent loading for long span girders

For simplicity, a blast load acting over the span of a component is typically considered to act as a uniform load. The load magnitude and its variation with respect to time may be determined by any number of methods such as work equivalency, a weighted average over a subjected area, or simply selecting the largest pressure and impulse acting on the component. In actuality, depending on the geometry of the component and its surroundings, as well as the standoff and orientation of the blast source, blast loads are likely to vary over the area of the component being analyzed. While in some cases it may be quite reasonable to approximate an applied blast pressure as acting uniformly over a component, this assumption becomes unrealistic as the variation in loading becomes large.

The pressure acting on a surface as a result of a blast is related to the standoff from the blast and the angle of incidence of a line from the blast source to a point on that surface. For example, consider a long-span girder, on the order of 80–160 feet, such as those found in highway bridges, subjected to a blast located some at some distance perpendicular to its longitudinal axis. The standoff varies significantly from the midspan to a point at the end of the girder, and the angle of incidence also substantially changes. Both of these factors contribute to creating a significant pressure gradient over the length of the girder. With a relatively long structural member subjected to a significant pressure gradient, it is unrealistic to utilize a uniform load to approximate the actual behaviour. Analytical evidence of this concept is presented later in Section 4. The concept of using a single uniform load to approximate the distribution of pressure over a blast loaded girder is illustrated below in Figure 1.

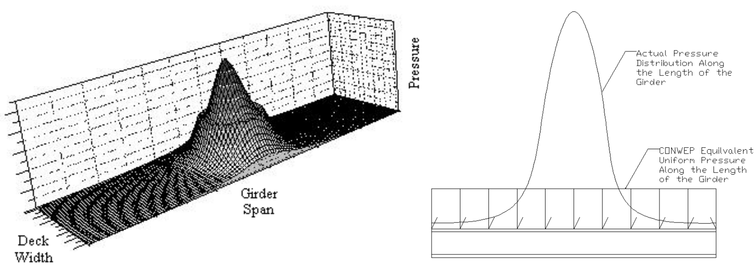

Figure 1: Distribution of blast pressure over a long span girder.

3 Development of dynamic analysis parameters for SDOF beams subjected to multiple uniform loads

In order to perform an SDOF analysis of a girder, system parameters such as stiffness, mass, ultimate resistance (load causing formation of a collapse mechanism), and equivalency factors equating the real system to the idealized system must be determined. The values of these parameters are subject to assumptions made about the displaced shape of the component under loading. Several choices exist for formulating these parameters. This research uses the displaced shape of the component under a static load of the same form as the dynamically applied blast load. The selection of this displaced shape corresponds to the recommendations made by Biggs [2] and is commonly accepted as the current state-of-practice. Examples of parameter calculations, along with tables of various system properties and transformation factors, can be readily found in several sources such as dynamics textbooks (e.g., Biggs [2]) and the Army TM5-1300 [4], a valuable reference for analysis of structures subjected to blast loading.

This research focuses on formulation of system parameters for beams subjected to a series of uniform loads of different magnitudes. Development of these parameters is performed in a manner consistent with the methods employed by Biggs [2] for one-way components. The first step in the process requires calculation of the static displaced shape. Figure 2, shown below, is an illustration of the loading condition which is used to replace the uniform equivalent load. Lines are used to differentiate the regions associated with the different load magnitudes. Different continuous functions within each load region describe the variation in transverse displacement with position. Continuity of the beam can be used to relate the expressions in each of the different segments.

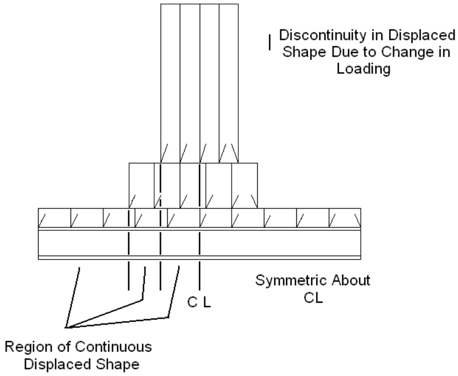

Figure 2: Loading condition diagram.

The SDOF stiffness is calculated as the reciprocal of the peak deflection of the static displaced shape. Multiple stiffness values are determined based on changing displaced shapes that occur as a result of the formation of plastic hinges. Resistance levels that form the bounds of these stiffness regions are calculated using plastic analysis techniques to determine the load level at which plastic hinges form. Depending on the selected boundary conditions (e.g., fixed or simple), two or three stiffness regions may exist. In order to effectively utilize these defining characteristics, load and mass transformation factors equating the real and idealized systems must be formulated. The factors account for the variation of mass and load over the displaced shape and are determined in accordance with eqns (1)–(3) below. In these equations, M_e is the mass transformation factor, m is the mass per unit length of the beam, $\phi(x)$ is the normalized displaced shape of the beam (i.e., peak deflection is scaled to a unit value), L_f is the load transformation factor, w, c, and p are the applied distributed loadings, respectively, in each region, L is the beam length, and L_{mf} is the load-mass transformation factor.

$$M_e = \int m \cdot \phi(x)^2 \quad (1)$$

$$L_f = \frac{\int_0^{nL} w \cdot \phi(x) \cdot dx + \int_0^{(j-n)L} c \cdot \phi(x) \cdot dx + \int_0^{(1-j-h)L/2} p \cdot \phi(x) \cdot dx}{(w + c + p) \cdot L} \quad (2)$$

$$L_{mf} = M_e / L_f \quad (3)$$

Each integration involving the displaced shape *ϕ(x)* must be performed piecewise and correlated with the appropriate length over which that displaced shape is valid. The appropriate load acting over that displaced shape must also be used, and the resultant of the entire load is required in the denominator of Equation 2. The evaluated mathematical expressions, including the displaced shapes, are not shown here because of their algebraic complexity; however, they have been derived in a manner that allows for changing of the lengths over which the different uniform loads act in order to account for blasts of differing distributions. Development was performed separately for fixed and simple boundary conditions. Details of the resulting expressions for the various analyses parameters can be found in Gannon [5].

4 Comparisons of loading methods using SDOF and finite element modelling

Current practice for component analysis using SDOF systems is to utilize a uniform equivalent load as computed using a program such as CONWEP [3]. Comparisons with SDOF models that allow for a variation in the applied loads as defined above are presented here to illustrate the effectiveness of this technique. Additional comparisons are made to finite element beam models that allow for a detailed variation in the applied load to be prescribed. The program SBEDS is used to calculate the response of SDOF models of steel bridge girders subjected to the uniform and multiple uniform loadings.

To illustrate the differences in loading techniques for long spans, a steel girder with the properties shown in Table 1 was subjected to TNT equivalent explosives of a magnitude on the order of a vehicle bomb. Standoffs of 12 and 20 feet were examined. The girders studied were assumed to be fully braced, and effects of the deck, such as added mass or composite action, were not considered.

The result of primary interest, which can be obtained from an SDOF analysis, is the midspan displacement history. In this case, flexural behaviour was modelled, and corresponding displacements were determined. Figure 3 is a plot of midspan displacement histories of an 80-foot girder subjected to 2000 pounds of TNT at a standoff of 20 feet determined using an SDOF model with a

CONWEP [3] uniform equivalent load, an SDOF model using the multiple distributed loads presented previously, and an ANSYS-LSDYNA [1] beam model using a series of uniform loads taken as an average of the CONWEP [3] pressure and impulse distribution along the girder length (a different series than used for the SDOF model). An 8-foot width was used for the tributary width, and a 32-foot width was used to determine the CONWEP [3] reflecting surface area. A steel yield strength of 50 ksi under static loading rates was assumed. This value was modified for material over-strength and increases due to strain rate effects to give an effective steel yield strength of 62.5 ksi.

Table 1: Properties of studied steel girder.

Property	Value
Girder Depth (in)	72
Web Thickness (in)	1
Area (in^2)	168
Moment of Inertia (in^4)	150408
Plastic Section Modulus (in^3)	4680
Weight (lbs/ft)	571.7

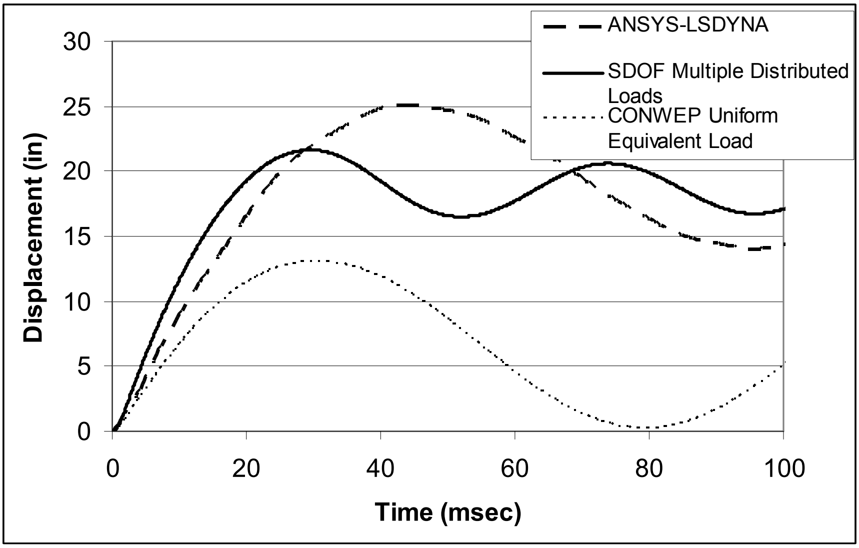

Figure 3: Midspan flexural displacement history of an 80 foot girder subjected to different loading types.

Several girders were examined to provide a range of data points for comparison of the available loading techniques. Girder parameters and explosive loadings were held constant, with standoffs of 12 and 20 feet considered. In order to include the importance of the load variation with position, multiple span lengths were included in the study. Lengths of 80, 120, and 160 feet were studied. These lengths encompass the majority of spans of typical steel girder highway bridges for which the multiple distributed loading may be most appropriate. The CONWEP [3] reflecting surface was assumed to be the same length as the span under consideration. Table 2 shows the calculated peak displacements using the various loading alternatives under consideration. The values in this table include the peak displacements from each curve shown in Figure 3 above.

Table 2: Comparison of peak flexural displacement values of girders using various modelling techniques and loadings.

Loading/analysis technique	Span	Standoff	Peak displacement	Error relative to ANSYS-LSDYNA
	(Feet)	(Feet)	(Inches)	(%)
CONWEP UEL[1]	80	12	19.7	-62.9
Multiple Distributed Loading	80	12	32.1	-39.6
ANSYS-LSDYNA	80	12	53.1	N/A
CONWEP UEL	80	20	13.1	-47.8
Multiple Distributed Loading	80	20	21.6	-13.9
ANSYS-LSDYNA	80	20	25.1	N/A
CONWEP UEL	120	12	27.5	-69.1
Multiple Distributed Loading	120	12	101.9	14.4
ANSYS-LSDYNA	120	12	89.1	N/A
CONWEP UEL	120	20	20.6	-58.0
Multiple Distributed Loading	120	20	38.5	-21.5
ANSYS-LSDYNA	120	20	49.1	N/A
CONWEP UEL	160	12	36.4	-64.3
Multiple Distributed Loading	160	12	110.3	8.2
ANSYS-LSDYNA	160	12	102.0	N/A
CONWEP UEL	160	20	29.3	-62.2
Multiple Distributed Loading	160	20	95.1	22.8
ANSYS-LSDYNA	160	20	77.4	N/A

[1] UEL denotes uniform equivalent load.

Review of the error relative to the peak midspan displacement determined by an ANSYS-LSDYNA [1] FEM, shown above in the last column of Table 2, clearly demonstrates that it is inaccurate and inappropriate to use a CONWEP [3] equivalent loading to characterize a blast pressure distribution over a long span.

The large pressure and impulse gradients are not effectively captured using the work equivalent method included within the software. It should be noted that it may be possible to more closely match the characteristic displacement using another form of uniform loading; however, further study would be required to devise a proper method for calculating the equivalent pressure and impulse.

The results shown in Table 2 clearly indicate that the response predictions based on the multiple uniform loadings are more accurate than the corresponding values obtained using the CONWEP [3] uniform equivalent loading when compared to the ANSYS-DYNA [1] solutions. While a certain degree of error still exists, response predictions compare more favourably to the finite element analyses, and the level of effort required to achieve these results is comparable to that used when approximating the load as acting uniformly over the span.

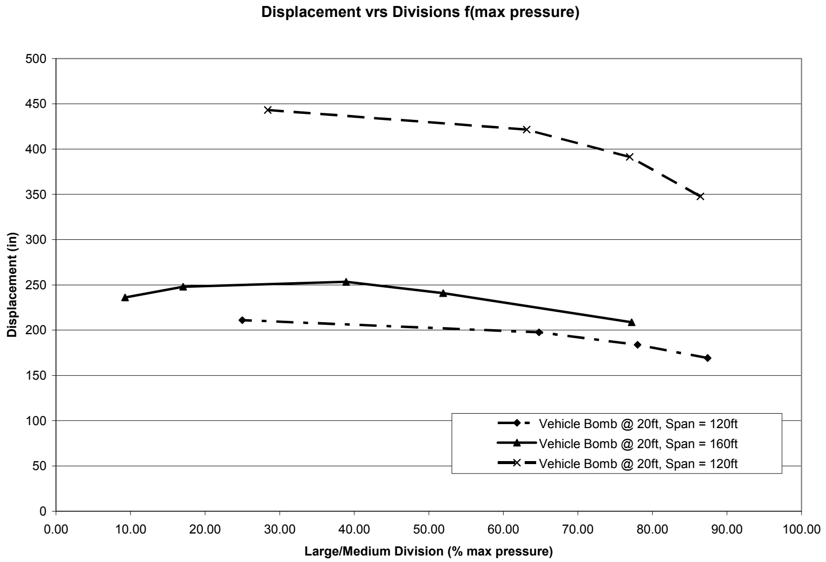

Figure 4: Peak midspan displacement versus relative length of multiple distributed loadings.

One consideration which is of importance to the use of multiple distributed loadings is the points at which the pressure gradient is approximated by breaks from one uniform load to the next. The model presented in this paper uses three distributed loads and requires divisions at 2 locations (on each side of girder midspan because of the symmetry assumed in these examples). The average pressure and impulse must then be determined for each uniform load over the area in question. If the location of these breaks is modified, slightly different dynamic system parameters would be calculated, and, therefore, a different midspan displacement would be obtained. Figure 4 illustrates different midspan displacements which would be calculated based on alternate selections of break points. In Figure 4, the location of the break between the smallest and next largest distributed loads is held constant, and the division between the largest and next largest distributed load is represented on the x-axis as a percentage of the peak blast pressure. A chart such as the one shown below can easily be generated for a range of system configurations under study, and a break point can be chosen such that conservative answers are determined by SDOF modelling. This paper has used a break point between the largest and next largest magnitude distributed loads of 45% of the peak pressure. An alternate break value could be chosen, but the relative accuracy of the multiple distributed loading method, compared to ANSYS-LSDYNA [1] analyses, would be approximately the same despite slightly different displacements values for each system.

5 Conclusions

It has been shown that for as the analysis of long-span girders, a series of uniform loads of different magnitudes is more appropriate for characterizing an applied blast load than a uniform equivalent load. Although mathematically the expressions for determining relevant system parameters are more cumbersome for a system subjected to multiple uniform loads, they can be easily written into spreadsheets or mathematical codes for quick evaluation. The added accuracy over a single uniform load, as demonstrated by comparison to FEM using a more detailed description of load, may be valuable in analytic studies or design where confidence in results can be used to reduce conservatism. The method of load description presented in this paper was effectively utilized in parametric studies of bridge girders under blast loading for a recent pool-funded study conducted by The University of Texas at Austin under the supervision of Dr. Eric Williamson. The purpose of that study was to determine effective methods of mitigating risk of failure of in-service highway bridges and to identify effective design concepts which could be used to improve blast resistance of future structures. A large number of SDOF models were evaluated to form a basis for the evaluation of different design and retrofit concepts. This method of blast pressure description was useful in part because it provided a method of load relief by using a load path approach. Because the analysis considered load variation over the length of a girder, failure of portions of the deck, which were loading the supporting girders, was readily modelled. A more accurate representation of the blast load acting on a girder or set of girders allows for an improved understanding of structural response and a more useful set of analytical results. Furthermore, because SDOF models are utilized, the time needed for analysis is less than that which would be needed for detailed finite element studies. Thus, the proposed blast load modelling alternative offers the advantage of increased accuracy over typical SDOF analyses while maintaining simplicity in the model development. While more advanced methods of analyses are needed for more accurate response predictions, the proposed method is well suited for initial design and for parametric studies that are often essential to the design process.

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