Loading and dynamic behaviour of bridges

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Loading and Dynamic Behaviour of Bridges

Chargement et comportement dynamique des ponts

Lasten und dynamisches Verhalten von Brücken

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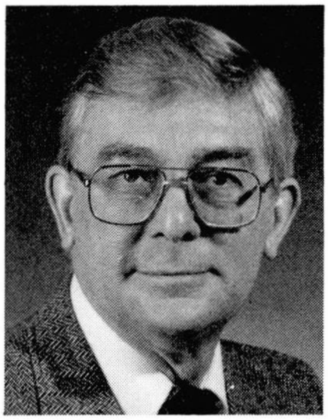


Roger Green, born 1934, holds degrees from London, Queen's-Kingston, Waterloo, and Texas. He has carried out research into bridge behaviour for the past two decades. Topics of interest include dynamics, thermal effects, stability and foundation design.

SUMMARY
Trucks crossing bridges give rise to both static and dynamic effects. This paper describes these effects, including truck-bridge interaction, dynamic response of bridges, and superposition of static and dynamic effects. Modes of vibration are discussed. Recommendations as to how the dynamic response of longitudinal bridge girders may be evaluated are given.

RÉSUMÉ
Les camions circulant sur les ponts provoquent des effets statiques et dynamiques. Cet article décrit ces effets, y compris l'interaction camion-pont, la réponse dynamique des ponts, ainsi que la superposition des effets statiques et dynamiques. Les modes de vibration sont discutés. Finalement, des recommandations sont données dans le but de pouvoir évaluer la réponse dynamique des poutres longitudinales de ponts.

ZUSAMMENFASSUNG
Lastwagen erzeugen beim Überqueren von Brücken sowohl statische als auch dynamische Effekte. In diesem Artikel werden solche Effekte beschrieben, unter anderen die Wechselwirkungen zwischen Lastwagen und Brücke, das dynamische Verhalten von Brücken und die Überlagerung von statischen und dynamischen Wirkungen. Diskutiert werden Formen von Schwingungen. Empfehlungen zur Beurteilung des dynamischen Verhaltens von Brückenlängsträgern werden gemacht.

1. INTRODUCTION

The prediction of the response of bridge structures to traffic load is essential if design or evaluation for fatigue or strength are to be completed with any confidence. Measurement of such response of bridge structures has been an ongoing activity in Ontario for the past 25 years [1-4]. These studies have generally been carried out on short and intermediate span structures and have addressed static, dynamic and bridge-vehicle characteristics.

Most bridge design practice avoids a direct treatment of the dynamic response of superstructures for various vehicular loading conditions. Static force effects of typical traffic or of a design truck are increased to account for bridge-vehicle interaction. Usually the increase is taken as being a function of static load, span length, loaded length and member under consideration [5]. Depth to span ratios may be limited to ensure sufficient static stiffness.

1.1 Basic Requirements

The strength of a structure or component thereof under extreme loads, the ultimate limit state, or moving truck traffic over a defined period, the fatigue limit state, is a function of:

- the resistance of the components or structure
- the static load distribution characteristics of the structure
- the dynamic load distribution characteristics of the structure
- the static load of the truck or trucks
- the dynamic load associated with the truck or trucks
- the dynamic interaction between trucks and structure, present for some structures and frequencies
- the force distribution developed in simple and continuous structures as a consequence of inertia forces.

The resistance of components or structure for a known geometry and displacement history appear to be well established with many stress concentrating geometries known. The S/N resistance relationships for such cases have been documented [6]. Examples are given as Figure 1.

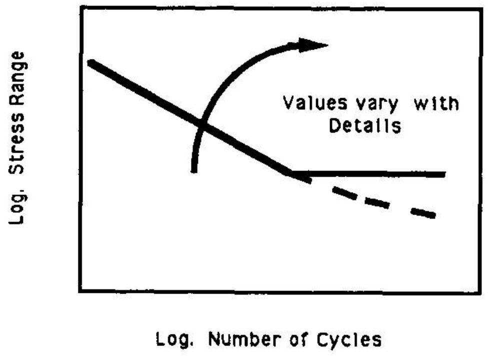
2. THE TRUCK SYSTEM

If a truck travels along a smooth rigid riding surface, the tires will apply a constant force to the surface. This constant tire force is an idealization which will change in the presence of any external force such as wind, braking, steering or pavement undulation. The tire force applied to the surface will have the form of a static force plus a time-dependent force.

As such a truck crosses a bridge, the riding surface will displace and a dynamic interaction between truck and bridge may occur. Thus, the vehicle and superstructure are coupled (Figure 2). The degree of interaction will be a function of the dynamic characteristics of both truck and bridge, and the pavement undulation and discontinuities.

2.1 Static Load Distribution

Recent studies by Hutchinson [7] have considered the distribution of GVW (GV Mass) between axles for bulk haul trucks and tractor trailer combinations. Many of these combinations use an air lift axle which is used when the truck has payload. In general, the measured GVW corresponded to the legal limit.



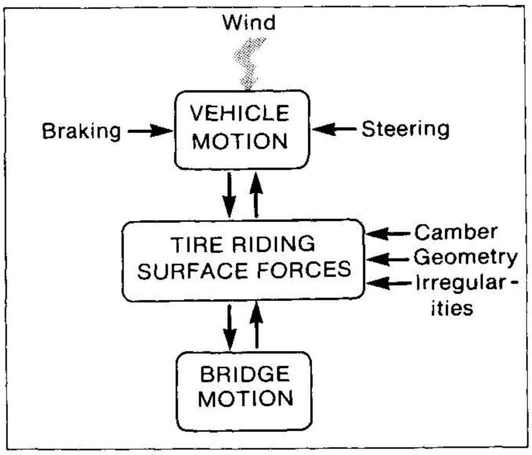


Figure 1 Typical S-N Curve

Figure 2 Vehicle-Bridge System

However, axle loads for the rear tandems were greater than the legal limit with values greater than 1.20 of legal being typical. The bending moment due to this uneven distribution of axle load was 1.15 greater than that due to a legal vehicle for spans up to 20 metres. Extreme values of axle load are up to 1.25 times the legal limit for trucks with fixed axles and 1.45 for trucks incorporating air lift belly axles.

The bending moment values resulting from trucks with extreme axle loads are of design significance and may be 40 percent greater than the calculated legal value. The stress range may be 3 times that due to a legal truck. Overloaded trucks are related to the industry being served, the degree of enforcement and the locality. Thus, average truck populations will not be typical in regions of heavy industry.

2.2 Dynamic Axle Loads

Papagiannakis has studied the effects of suspension type, vehicle speed and pavement roughness on the dynamic variation of static vehicle loads[8]. The test vehicle was identical to that used by Woodroffe et al. [9] and allowed change of suspension type and number of axles with relative ease. Used were a walking beam suspension and a multileaf spring suspension in the trailer and tractor, respectively. Typical axle load waveforms are given for leading and trailing axles of the tandem assemblies in Figure 3.

The results given are for pavement conditions and do not include expansion joints or bridge skew. Dynamic load waveforms for tandem axles tend to be in phase and to have similar amplitudes for both walking beam suspensions and leaf spring suspensions. The spectral density of dynamic load indicates that for smooth pavement and modest speed (17 m/sec), frequencies of 3 Hz and 5 Hz dominate and relate to bouncing of the sprung mass on the tires and to wheel eccentricity. Similar data for higher speeds and greater pavement roughness indicate that 3 Hz is the dominant frequency. The standard deviation of axle load is a direct function of suspension type for a given pavement

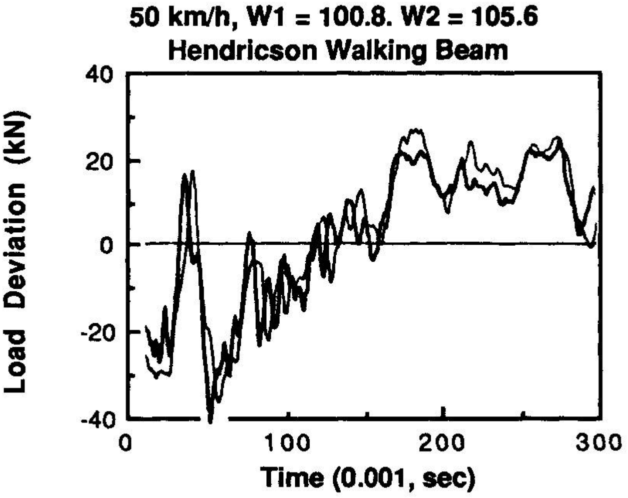


Figure 3 Axle Load Waveforms

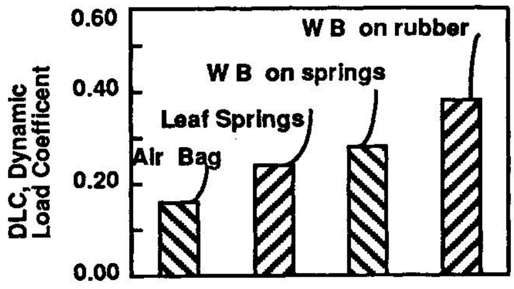
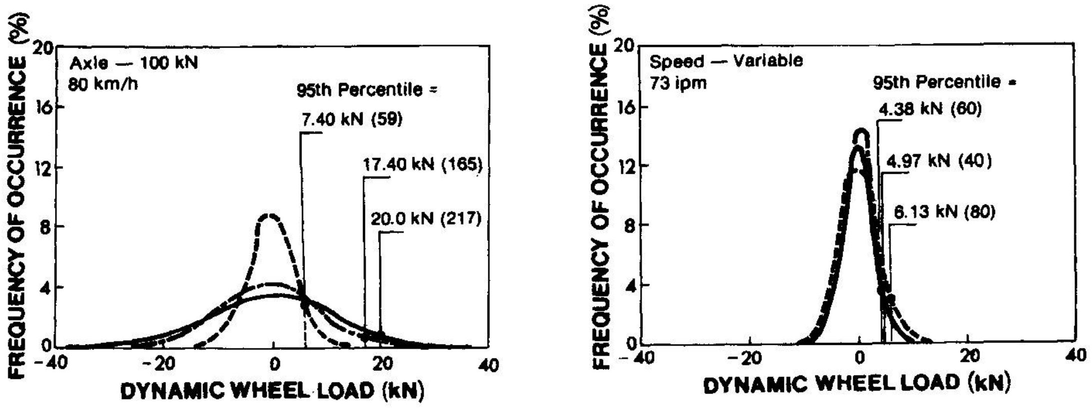


Figure 4 DLC-Various Suspensions

roughness (Figure 4). The deviation indicates that it may be beneficial to modify walking beam suspensions in the interests of reducing dynamic effects. The standard deviation of axle load increases with increasing truck speed and road roughness (Figure 5).

2.3 Ontario Test Data, 1956/7

In 1956/7, a group of 52 bridges known to vibrate were tested using a calibration truck of known weight and free flowing traffic [2]. Only midspan deflection data were obtained. Vibration of the structures indicated a first longitudinal flexural frequency, a forced flexural frequency (2 to 3 Hz), or a first torsional frequency. Dynamic effects tended to be a maximum in the 2 to 5 Hz range. For increasing GVW, the dynamic effects per unit weight decrease for truck length less than span length.



a) Variable Roughness b) Variable Speed

Figure 5 Dynamic Wheel Loads with Variable Roughness and Speed

There was appreciable variation in the dynamic deflection values for a given bridge or between bridges. This variation is due in part to differing pavement roughness and differing bump characteristics, and to the initial conditions of a truck entering the structure. Static span to depth limitations were insufficient to restrict noticeable vibration.

2.4 Ontario Test Data, 1980

Twenty-seven structures were tested using representative test vehicles approaching legal limits (241 kN to 580 kN). Fourteen steel spans of 22 to 122 m, and ten concrete spans of 16 to 41 m were tested. The test procedure and bridge details are given in Reference [1] . Approaches, joints and deck surface were in good condition. The main objective of these tests was to determine the dynamic amplification of main longitudinal members.

2.4.1 Dynamic Characteristics

Between six and 12 nodes of vibration of longitudinal flexure, torsion and transverse flexure could normally be identified for longer span, continuous bridges. All components of the structure resisted the action of static and dynamic load. The transverse static response distribution showed that bracing and barrier walls provide substantial stiffness under the action of a single truck.

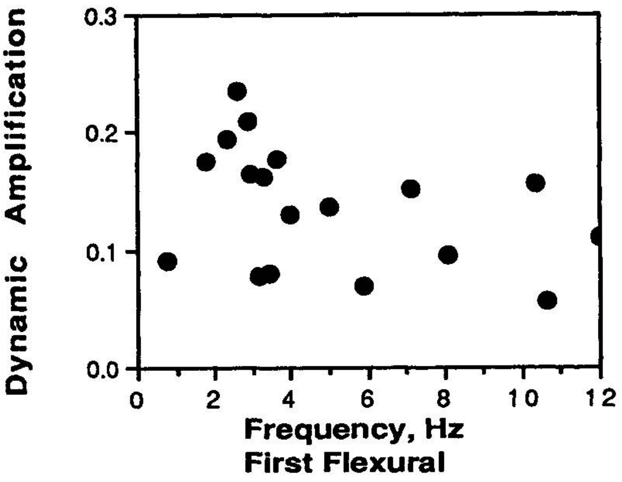


Figure 6 Mean Dynamic Amplification - Frequency

2.4.2 Dynamic Response

Statistical data of dynamic amplification are available. These include all runs by single test vehicles and by other traffic at all speeds in any one lane of each bridge. The mean values of dynamic amplifications are not large (Figure 6) with approximately one-third of the values less than 0.1, and only one-tenth greater than 0.2. Some individual values of amplification, greater than 0.5, were observed. The coefficients of variation are variable and large, with values between 0.56 and 1.11 and a mean of 0.85 for a single lane.

2.4.3 Truck Suspension and Weight

Test vehicles TV1 and TV2 were similar in overall dimensions and weight. TV2 had an air suspension, while TV1 had leaf springs. The mean dynamic amplification due to TV2 was only about 60 percent of that for TV1. The air spring and parallel shock absorber suspension system presumably provides damping under all conditions, whereas the leaf spring assembly will only absorb energy for conditions of large displacement or high rates of loading.

2.4.4 Overall Results

The mean dynamic amplification for all runs generally decreased with an increase in the weight of trucks for spans greater than about 30 m (Figure 7). If the product of truck weight and dynamic amplification is used as a measure of total dynamic load associated with a vehicle, Figure 8 shows the dynamic load corresponding to the data of Figure 7. The dynamic load shown is sensibly

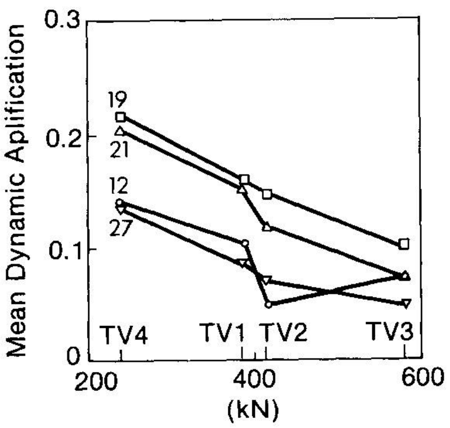


Figure 7 Mean Dynamic Amplification-Weight

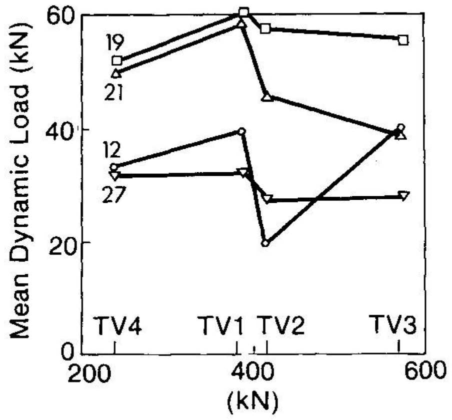


Figure 8 Mean Dynamic Load-Weight

constant with test vehicle weight, with different magnitudes corresponding to different pavement irregularity.

Values of mean total dynamic load for heavy multi-axle trucks have been observed to vary between 30 kN and 120 kN. Perhaps future codes will specify a dynamic load, rather than dynamic load allowance, which is a constant for a wide range of vehicle geometries and loads so reflecting the influence of numbers of axles carrying a load rather than just the total load.

3. LOAD DISTRIBUTION CHARACTERISTICS

3.1 Static Characteristics

The static load distribution characteristics of a bridge cross section are a function of the restraint to distortion. The transverse stiffness of the riding surface (deck) and any transverse bracing will tend to control distortion and hence static load distribution. For example, the static load distribution characteristics to a multibeam structure common in Canada and the United States are shown in the form of transverse influence lines for midspan moment per longitudinal girder in Figure 9. The effect of curbs and cross bracing in improving the load distribution characteristics, (case NM4), is clear.

Also given [10] was a comparison between observed and calculated deflection at midspan. Agreement is good for the shape of the transverse distribution of deflection for finite element models, NM4 and NM2 (not shown). Both these models include vertical cross bracing to minimize distortion. Absolute values of observed and calculated deflection differ, due to a longitudinal restraint at the supports.

3.2 Dynamic Characteristics

In general, the static and dynamic load distribution characteristics of main members of bridge structures are not identical [1]. Deflection-time data from a six girder bridge are shown in Figure 10. For girder 6, a location directly beneath the truck load, dynamic effects are about 60 percent of static. However, for girder 1, static effects are less than the dynamic. The superposition of the transverse static and dynamic effects is given in Figure

11. Interior girders are shielded from the maximum effects of torsional vibration. Such torsional modes will add to the cyclic deformation experienced by any cross bracing.

3.3 Moment Envelopes

The longitudinal distribution of dynamic effects and static effects can be dissimilar. The inertia forces acting on a vibrating continuous beam are proportional to the sum of the products of frequency (squared), the mass, and the modal shape. The magnitude of force is a function of the contribution of a given frequency to the motion of the beam.

Kope [10] calculated the moment envelopes which result when the inertia forces from several modes are assumed to contribute equally, with modal participation proportional to the inverse of frequency squared. Figure 12 shows the distribution of dynamic moment due to self weight and consideration of vibration modes 1 to 4 for a two span bridge beam system. The distribution of moment is nearly uniform throughout the length of the two span system, and has a form quite different from the static effects of traffic load.

Moment envelopes for a two span beam are given in Figure 13. Two forms are used to describe dynamic allowances; one which is proportional to static effects and the second which is a uniform allowance whose magnitude is equal to the maximum design static effect. In positive moment regions little difference exists between the two allowances. However, in moment regions with minimal moment, the dynamic effect due to inertia forces is large in comparison to the static effect.

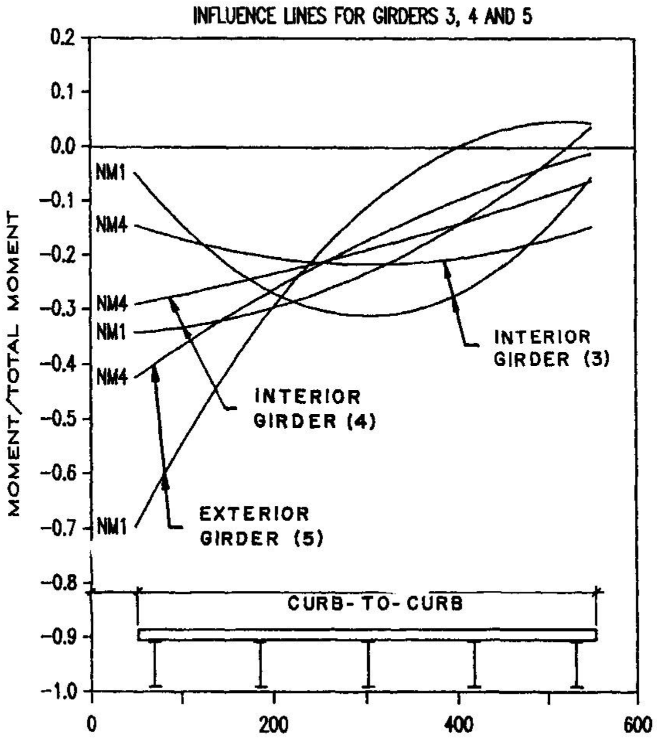


Figure 9 Influence Line for Midspan Moment

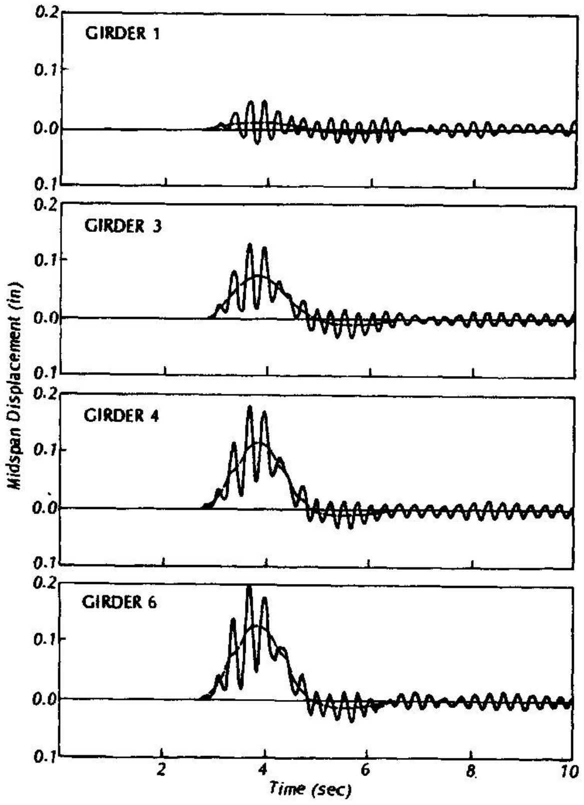


Figure 10 Beam and Girder System

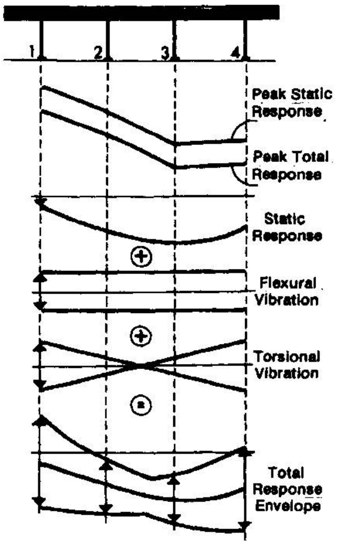


Figure 11 Beam Vibration

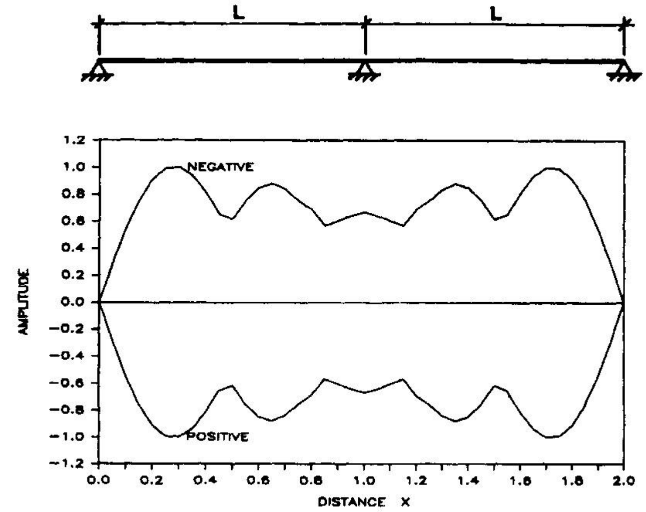
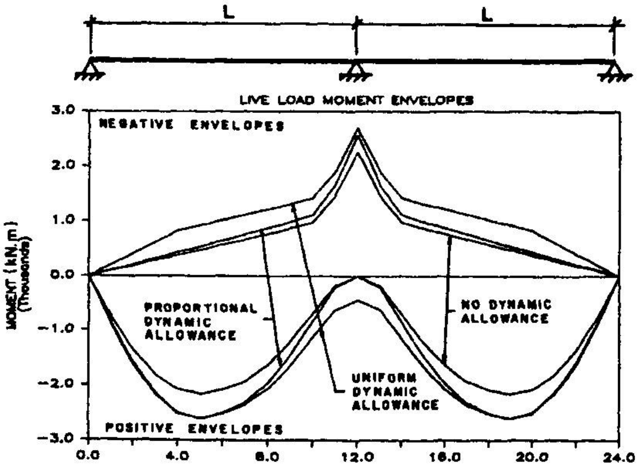


Figure 12 Distribution of Dynamic Moment

3.4 Stress Range

Figure 14 illustrates this effect of enhanced dynamic influence in continuous spans by comparing (a) an observed stress range and (b) a code specified load model stress range. The amplification of the unit positive static effect is 0.2, however, the observed amplification of the negative response of 0.3 is also 0.2. The code model amplification would be of the order of 0.06. Thus, the observed stress range is 1.70 units and code stress range is 1.56 units, a difference worth noting, if the range is raised to either the power of 3 or 5.



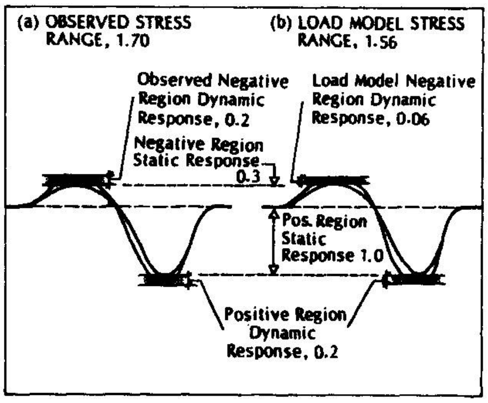


Figure 13 Live Load Moment Envelope

Figure 14 Various Stress Range

3.5 GVW

Results from Ontario studies tend to indicate that the mean dynamic amplification for a given bridge is a function of truck GVW (Figure 15). This implies that dynamic effects per unit weight decrease as the number of axles supporting the load increases for truck lengths less than the span length. The magnitude of such mean values are a function of two main features:

- pavement irregularity
- frequency match between truck and bridge.

For frequency, Billing [1] and Cantieni [11] have shown that dynamic effects do increase over the bridge frequency range of 2 to 5 Hz, a range close to the truck-on-tire frequency. The observed mean dynamic in this frequency range is statistically different to values observed outside the range, and have a global mean which is approximately 50 percent more than for the non frequency match range case.

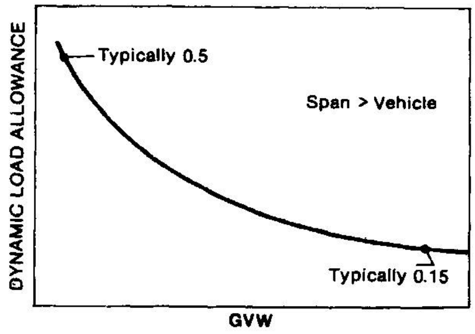


Figure 15 Dynamic Load Allowance - GVW

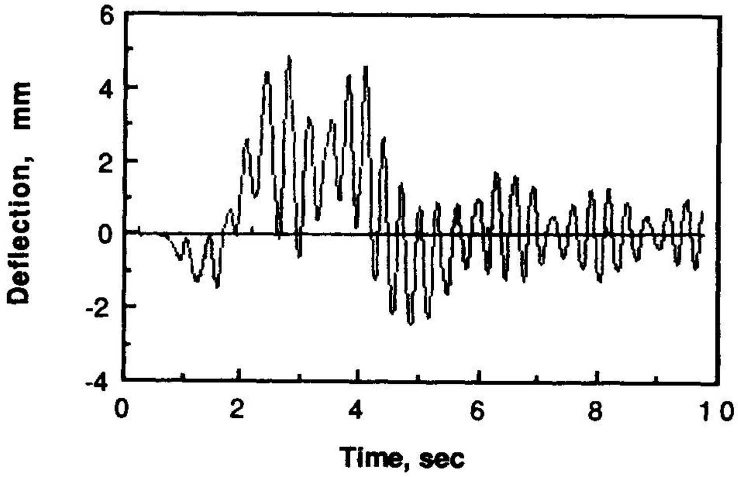


Figure 16 Deflection-time Response Continuous Span

4. STRESS CYCLES

Figure 16 gives the deflection-time trace for the midspan of the second span of a four span prestressed concrete slab bridge, continuous steel structures have similar responses. The two test vehicles each corresponding to legal loads followed each other. This lightly damped response exhibits a number of stress cycles under load and many cycles of free vibration where flexural-torsional beating exists. The results indicate one well defined stress cycle and many minicycles, which, for fatigue considerations, are also damaging and need to be included in any model for fatigue damage.

5. CONCLUSIONS

A truck crossing a bridge results in both static and dynamic effects. The prediction of static stress range in main members and connections can be carried out with ease if the static load distribution characteristics of the bridge superstructure are known. Simple amplification of static effects is a poor predictor of dynamic effects of vehicle load and the interaction of this load with the bridge. The dynamic fraction of vehicle load is a function of pavement irregularity and the lateral position of the vehicle. A frequency match may occur between a vehicle and bridge so amplifying the dynamic wheel load. Dynamic effects give distributions of force which differ from static effects and are also not proportional to static vehicle load. Load models for fatigue calculation of stress range should consider these dynamic effects.

6. ACKNOWLEDGMENTS

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