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Load Spectra for Bridge Evaluation

Spectre de charges pour l'évaluation des ponts

Lastspektren für die Bewertung bestehender Brücken

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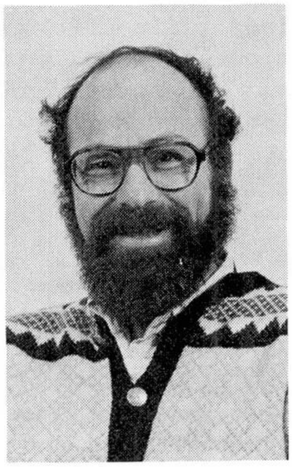

Fred Moses received a civil engineering degree from CUNY in 1960 and a Ph. D. from Cornell in 1963. Since joining Case Institute, Professor Moses has been active in structural optimization and reliability with special applications to bridge and offshore structures including loading, safety analysis and system reliability studies.

SUMMARY

Evaluating existing bridges can be more complex then designing new structures. It is suggested herein that bridge inspections should include load history as well as bridge condition. A recently developed weigh-in-motion technology reduces uncertainty by accurately determining records of truck weights, bridge response and repetitive stress-spectra. Reliability predictions can further assist decision-making by modelling fatigue failure and overall fail-safe capacity. Applications include inspection, posting, legal limits, enforcement, rating and permit assessments. Such evaluation-related problems can all benefit from improved load modelling and site-specific loading statistics formulated into a reliability model.

RESUME

L'évaluation de ponts existants peut être plus complexe que le calcul de nouvelles constructions. L'inspection de ponts devrait inclure l'étude des cas de charges antérieures ainsi que de l'état du pont. Une technologie récente, nommée „weigh-in-motion", est basée sur la détermination exacte du poids des camions, le comportement du pont et le diagramme des charges répétitives. Des prédictions fiables facilitent la décision par la création de modèles de rupture à la fatigue et de capacité globale rupture-sécurité. La méthode tient compte de l'inspection, de la signalisation, des limites légales, et des charges autorisées. De tels problèmes d'évaluation peuvent être étudiés à l'aide d'un modèle de charge et de statistiques de charges exprimées en un modèle de sécurité.

ZUSAMMENFASSUNG

Die Bewertung bestehender Brücken kann umfassender sein als die Projektierung neuer Brückenbauten. Im vorliegenden Bericht wird vorgeschlagen in der Brückenüberwachung auch die Lastenentwicklung und den Brückenzustand einzuschliessen. Eine neu entwickelte „weigh-in-motion" — Technologie vermindert Unsicherheiten durch eine sorgfältige Bestimmung der Lastwagengewichte, der Antwort — und der Spannungsspektren. Zuverlässigkeitsvoraussagen können weiter zum Entscheid beitragen, indem Modelle für das Ermüdungsversagen und die umfassende „failsafe"-Kapazität geschaffen werden. Die Anwendungen beinhalten Überwachung, Standort, die gesetzlichen Grenzen, Durchsetzbarkeit, Bewertung und Einschätzungserlaubnis. Solche Bewertungsmodelle können profitieren von verfeinerten Lastmodellen und objektbezogenen Belastungsstatistiken, dargelegt in einem Zuverlässigkeitsmodell.

1. INTRODUCTION

Repair, posting and replacement of bridge structures requires high expenditures. Such decision must distribute limited available resources considering public economy, safety and utility. The decision process reflects past experience, current technologies, cost limitations and future needs. Because safety is implicitly involved, risk estimations are present. The limited data and cost of acquiring more information to assist decision-making is important. New developments in low-cost data gathering which reduce uncertainties must be explored.

Bridge evaluation and rating combines field information and calculation models. At present, strength estimates are compared to load calculations to check acceptable allowable stress levels. The assessment uncertainties and reliability may be different from such parameters in new designs. This paper suggests that the checking and calculations for rating, repair and strengthening of existing bridges be altered based on bridge site, geometry, traffic and loading conditions.

New technological developments in data gathering and broad philosophical changes in design codes of practice should now be considered in bridge assessment and evaluation. The data gathering refers to automated methods for rapidly and economically acquiring truck load information. The design technology includes reliability methods for calibrating acceptable safety margins. Advantages include a consistent basis for expressing load and strength uncertainties and improved economy for structures with high dead to live ratios typical of longer spans and older structures. AASHTO load factor design provisions were adopted to move towards these goals [1] and there is further study to refine design safety factors to reflect current heavy truck traffic and loads [2]. A reliability-based framework can produce significant benefits when assessing existing bridges. The issues to be resolved in these evaluation applications include the following:

- An existing bridge has a loading spectra that can be measured rather than extrapolated from planning models.

- Analysis assumptions such as load distributions and dynamic behavior may be verified by experimental observation. Also, self-weight can be estimated more accurately.

- Ultimate capacity rather than serviceability may be acceptable criteria for existing bridges.

- The optimum economic reliability changes for an existing structure compared to a new design. The cost of increased strength margins are usually much lower for new constructions and so the trade-off equations are different.

This paper primarily reviews two new developments to aid bridge assessment and rating:

1) The application of newly developed weigh-in-motion technology to obtain current traffic, loading and other bridge response data [3-6].

2) The use of reliability design methodology to aid the structural decision process [2, 7, 8].

2. LOADING ANALYSIS

For most short and medium span bridges, the critical loading is self-weight and heavy truck traffic. Self-weight can be accurately estimated from cores and recorded dimensions. Repetitive heavy vehicle load cycles, however, may induce fatigue damage, cracks and ultimately collapse. It is not uncommon for wheel load sensitive details to experience many millions of stress cycles. Main load carrying members also experience millions of load cycles as well as extreme occurrences that may cause instability, permanent displacement or collapse.

Each live load occurence depends on truck weight and dimensions, dynamic impact and intervals of adjacent vehicles (headways). In a critical component, stress range depends on load distribution and bridge dynamics which in design are estimated from simplified models. Present load specifications also reflect heavy truck traffic in existence many decades ago. Changes in truck traffic including heavier legal and permit vehicles and other modern trends are important. Comparisons should include:

- Increased gross weights. Unless accompanied by longer axle lengths, heavier vehicles induce greater longitudinal bending moments.

- Influence of closely spaced axles. Increased tandem and triaxial weight combinations significantly affect component stresses sensitive to concentrated wheel loads.

- Lighter bridges. Such recent designs are more prone to higher impact and dynamic response.

- Traffic increases. The frequency of platoons of closely spaced vehicles, superimposing their load effects, increases with higher volumes.

- Enforcement. There is concern that CB communication and by-pass options has decreased legal load enforcement. Little is also known about the efficiency of posting signs in restricting loads.

- Bridge lives. It is evident that initial estimates of 40-70 years for bridge lives are being surpassed. The current economic climate suggests little improvement in this regard.

2.1 Design Loads

Modern developments in bridge load modelling have produced changes in some design codes. The 1979 Ontario Highway Bridge Design Code completely revised the existing load tables [9]. Figure 1 compares the present AASHTO (U.S. - [1]) and Ontario design simple span longitudinal bending moments. The much larger Ontario mements were matched to loadometer data obtained in the early 1970's combined with a simulation model of truck headways [10] (The equipment available then did not permit undetected weighing or precise vehicle spacings. Such study is underway to further verify the loading models [11]). Other countries have also altered their loadings. In Great Britain, a fatigue spectra provided from field studies is used to check damage on a 120 year life estimate [12].

In the United States, several studies measured bridge stress spectra. Results were incorporated in the AASHTO fatigue checking provisions [13]. For example, a study for Ohio DOT and FHWA Surveyed 10 sites to give data on stress spectra, spacing behavior, dynamic response and girder analysis variations [14]. Recently, the electronic and computer equipment permits correlating bridge stresses with truck weight. This provides more accurate bridge loading data and the statis-

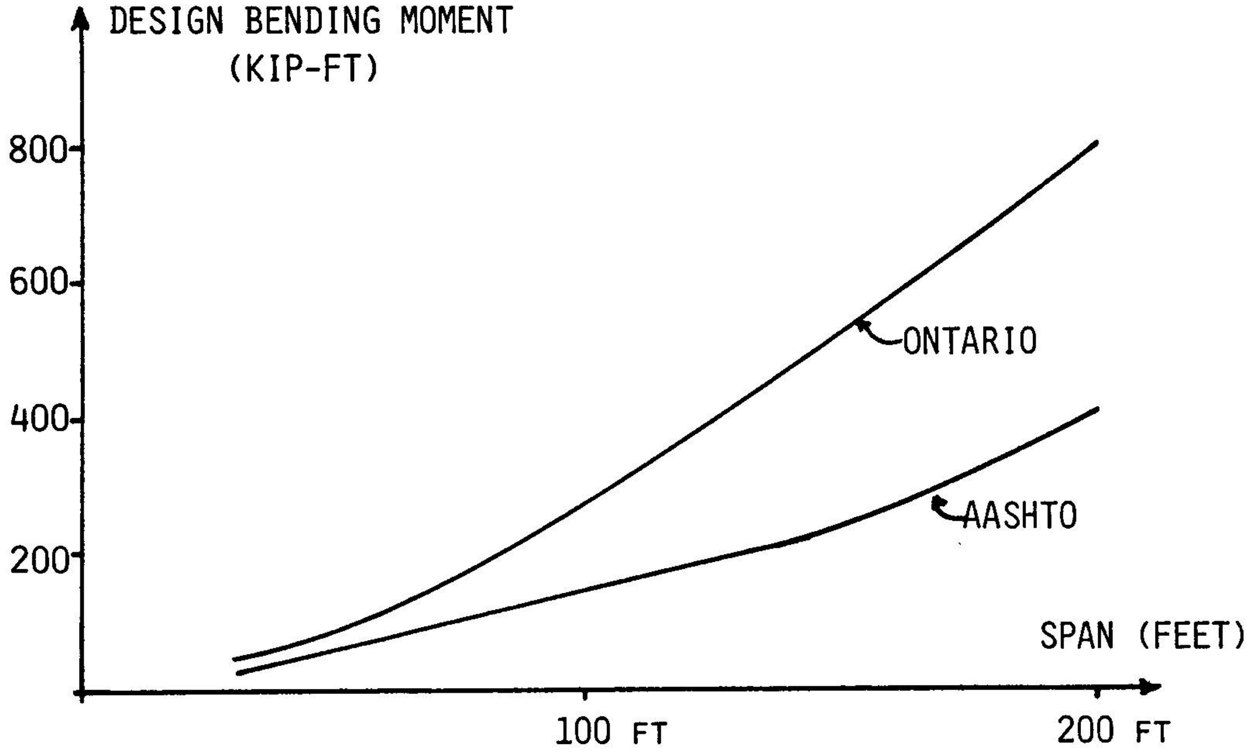

FIGURE 1 COMPARISON OF DESIGN BENDING MOMENTS FOR ONTARIO [9] AND AASHTO [1] BRIDGE SPECIFICATIONS.

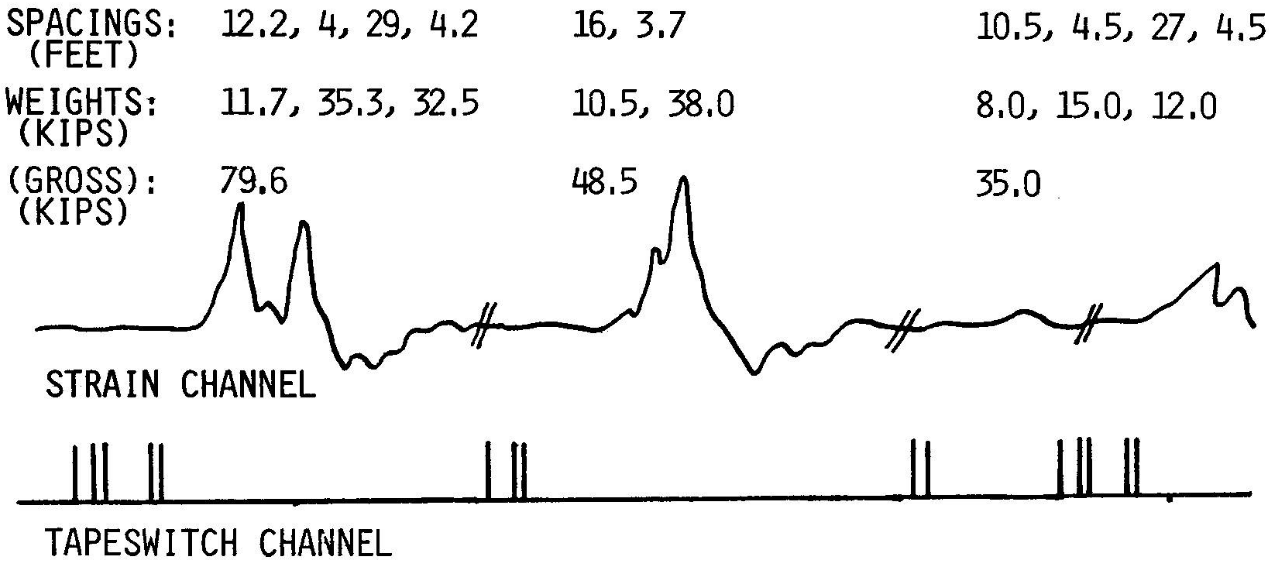

FIGURE 2 SAMPLE RECORD FROM WIM SYSTEM SHOWING BRIDGE STRAIN OUTPUT, TAPESWITCH SIGNALS AND AUTOMATICALLY PROCESSED TRUCK AXLE AND GROSS WEIGHTS, DIMENSIONS AND SPEEDS [4].

tics for reliability-oriented calculations. For bridge assessments, it gives a tool for specific on-site load spectra evaluation and to verify legal or posting conformance. This technique is described in the next section.

3. WEIGH-IN-MOTION TECHNOLOGY

For several years there has been world-wide interest in producing an undetectable system for automatically weighing moving trucks at normal highway speeds. A variety of pavement insert scales have been tested. These flexible plates respond to vertical forces and are calibrated to give histograms of recorded wheel loads. The problems encountered are due to scale flexibility and the "bounce" when a massive flexible vehicle moves on a rough pavement at high speeds. The vehicle is typically on the scale for only a portion of its natural period and large systematic errors may occur due to force oscillation. As a consequence, pavement scales are often restricted to low-speed sorting at busy weigh stations.

Avoidance of static scales is well recognized and by-pass routes makes most scales ineffective for obtaining accurate high-weight statistics [15]. As a consequence the author and his collegues extended the bridge measurement stress system to obtain truck weight information. The weighing system has reached the stage of relatively routine operation by the Ohio Department of Transportation [3, 4], the Federal Highway Administration [6] and other groups to monitor truck weights. Thus far, more than 50 sites have been surveyed.

Briefly, the weigh-in-motion (WIM) utilizes existing bridges as equivalent static scales. Trucks move at normal speeds and drivers cannot detect the weighing operations. Vehicle speeds and dimensions are obtained via tapeswitches bonded to the roadway. Bridge girder response comes from reuseable strain transducers clamped to steel flanges or bolted to concrete beams. The girder influence line provides a simulated strain record. By automatically matching the measured and simulated strains, the vehicle axle weights are obtained [3]. The data recording, monitoring and weight calculation is done by minicomputer in real-time in an instrument van usually parked beneath the bridge. To establish a relationship between strains and truck weight, a known calibration truck is used.

Sites monitored by this procedure have included single span and continuous steel girders and reinforced and prestressed concrete beams in all parts of the United States [6].

The WIM weighing accuracy has been verified by several studies comparing with static weighings. Also, at each site, repeatability is checked with the calibration truck and is usually less than 3%. The prediction accuracy for gross weights has shown standard errors less than 10%, which compares favorably with portable and other static weighing devices. It is most important for fatigue and bridge loading that the weight predictions are unbiased. The WIM surveys provide an important data source for load and fatigue spectra modelling.

Figure 2 shows a sample record from an Ohio site. The strain is actually a sum of several parallel girder responses. The vehicle combinations are also shown in Figure 2. A typical WIM loadometer survey is given in Figure 3. Weight spectra peaks correspond to loaded and empty vehicles. In addition to gross weights, the system outputs axle weights, vehicle axle dimensions, lane, speed and headway [4]. This data is important for constructing load models [2].

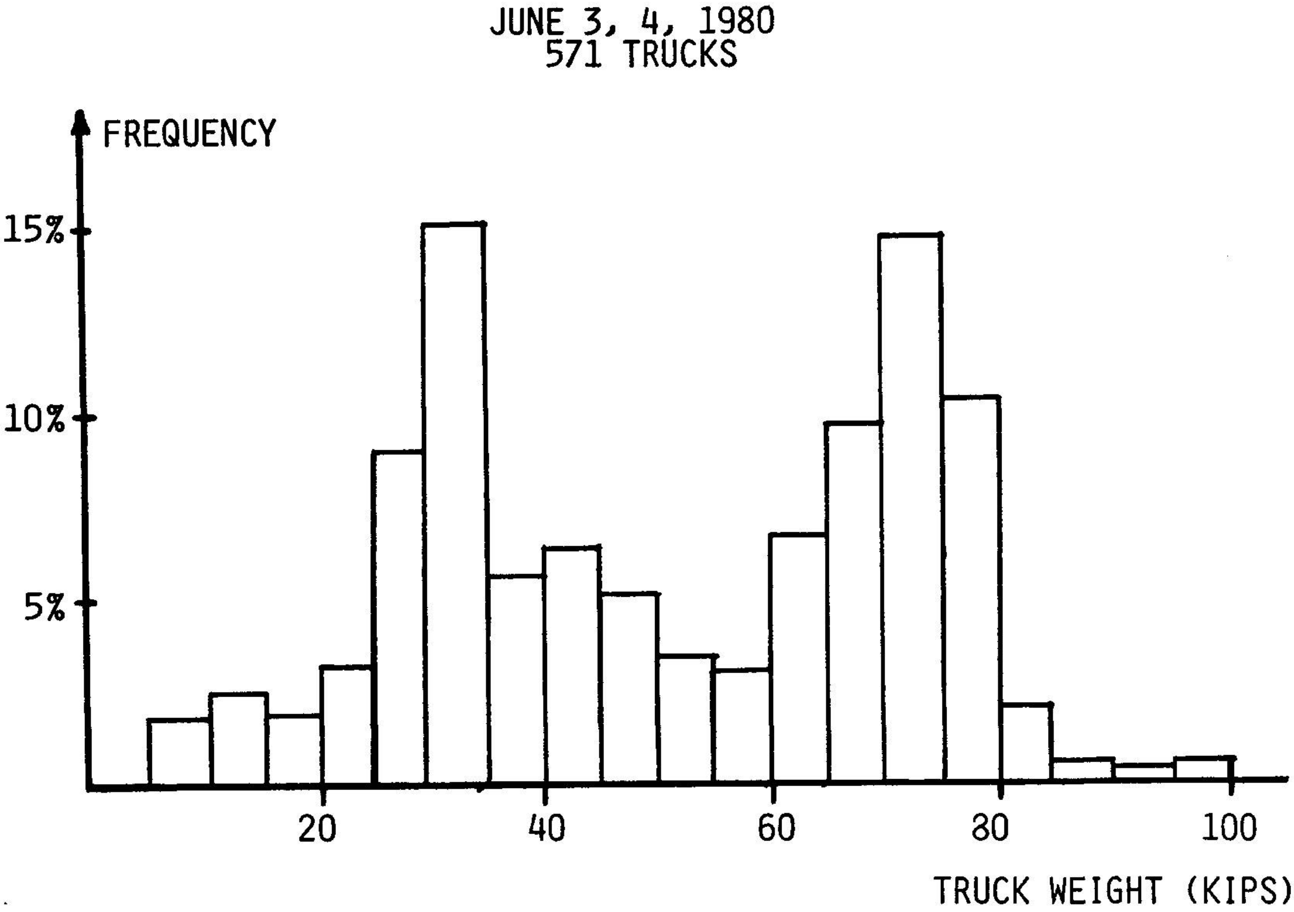

FIGURE 3 SAMPLE WIM GENERATED LOADOMETER SURVEY FOR GROSS TRUCK WEIGHTS [4].

4. FATIGUE ANALYSIS

The statistical data available from WIM technology can be utilized in several ways. For fatigue assessment the data can be expressed as a load spectra. Fatigue is a cumulative process in which each cycle adds damage until failure occurs. With several common assumptions the process can be incorporated in a risk evaluation. Assume a linear damage accumulation proportional to live load stress range. Thus,

Damage, $$D = \Sigma D_i \tag{1}$$

where: Σ - summation

D_i - damage due to single loading cycle

Using Miner's law, the damage is proportional to cycles to failure (N_i) to give:

$$D = \Sigma \frac{n_i}{N_i} \tag{2}$$

where: n_i - number of cycles of stress, S_i

Assuming N_i and S_i are related by a cubic damage rule gives [13]:

$$D = \frac{V}{c} \Sigma S_i^3 f(S_i) \tag{3}$$

where:
- c - constant from S-N fatigue curve intercept
- V - truck volume
- $f(S_i)$ - frequency of stress, S_i

Stress is proportional to truck weight so damage can be expressed in terms of the load variables. Thus, [5, 16]

$$D = \frac{V}{c} h\ I\ g\ m\ L \tag{4}$$

$f(S_i)$ - frequency of stress, S_i

where:
- h - superposition effect of closely spaced vehicles
- I - dynamic overload
- g - analysis variable (girder distribution)
- m - stress of nominal design vehicle

and

$$L = \Sigma(\frac{W_i}{W_n})^3 f(W_i) \tag{5}$$

where: W_n - nominal design vehicle weight

For an existing structure the load variables can be measured with WIM equipment. Alternatively, V, L and h can be extrapolated from statistics at similar sites, while g, m, and I are estimated from similar bridge types and spans. The fatigue variable c is based on laboratory tests for appropriate structural details [13].

4.1 Reliability Estimation

The fatigue model can assess reliability in a notional rather than precise actuarial sense. This is satisfactory for comparing diverse bridge locations and incorporating past experiences. If the failure damage is denoted as D_f (mean is 1.0), the risk (P_f) can be written as:

$$\text{Risk, } P_f = Pr[D > D_f] \tag{6}$$

Pr means probability. The uncertainties include material variables, C and D_f traffic variables L, h and V and bridge variables I, m and g.

The complexity of combining all the data in frequency distributions means approximate risk assessments must be used. Second-moment reliability approximations utilize means and standard deviations to obtain safety index (Beta-β) measures [8]. Let the failure function, g, equal:

$$g = D - D_f \tag{7}$$

and safety index, $\beta = \frac{\bar{g}}{\sigma_g}$ [mean ÷ standard deviation] (8)

The reliability measure, β, is suitable for comparing fatigue risks [5, 16]. Recent reliability studies have improved the safety index mode for deriving bridge code safety factors in Canada and Great Britain and other structural codes in the U.S. [7, 12]. A calibration with acceptable structures assures that past practice is incorporated in attaining uniform reliability criteria. Strength as well as fatigue provisions have been studied utilizing lifetime predictions of maximum loading. Two limitations in these developments affect bridge applications.

1. Truck loads are evolving over time, so past practice is not a satisfactory calibration criteria.

2. Code oriented reliabilities are suitable for single component checks, but fail-safe capacity including redundancy is important for bridge assessment. That is, a single component weakness may not cause collapse but loads are redistributed and the bridge is still functional. A fail-safe investigation requires nonlinear behavior. Computer models to predict response are available and results have been verified by testing [17].

   An example of fail-safe implications are found in the AASHTO provisions which permit lower fatigue stresses for nonredundant designs [1]. This is intended to restrict situations in which single element fatigue failure leads to collapse.

   Studies of component and system reliability have been reported for bridges and other structural systems [2, 18]. In bridge assessment, system reliability models may have even greater decision-making potential. It is suited for environments with limited economic resources and when decisions must often categorize bridge deficiencies and rank investment priorities.

5. APPLICATIONS

The previous sections demonstrated reliability-based techniques to combine current truck traffic, bridge loading and laboratory and field data in strength and fatigue assessments. The following topics consider these new developments.

5.1 Inspections

Funds for bridge inspections are limited, requiring optimum schedules. Typical bridge inspection concentrates on physical condition giving important strength information. Inspections should alsoinclude load data since safety checking compares loads with strength. Load assessment may include truck volume, unbiased weight spectra, bridge dynamic response and data on behavior and load distribution within the structure. These parameters are potentially available from WIM technology. Costs may be reduced by not acquiring all information at each inspection.

In cases where posting or extensive rehabilitation seem necessary, additional physical testing to verify strength may be done. The Ontario Ministry of Transportation has been especially active in testing a variety of bridges and benefits from improved verification greatly exceed testing costs [10]. Such testing is more than proof-loading but is done in conjunction with structural analysis to verify predicted behavior. Combined with load assessments, the adequacy of strength margins can be predicted.

Reliability calculations also have potential for establishing inspection strategies. Although fatigue life calculations are often not part of assessment, the reliability predictions can identify potential flaws and provide guidance for detailed field inspection. In addition, components with small fail-safe system reliability margins for load redistribution should also receive frequent and detailed field inspections.

5.2 Posting

Weight posting is warranted if an assessment determines a bridge lacks adequate strength. This is a difficult decision since posting will be obeyed by buses, fire trucks and other critical services. Hence, there is pressure not to be overly restrictive. Some commercial operators, however, may violate posting so listed limits should be low. Specific WIM surveys should study whether the public is obeying posting limits. Tighter control is needed if significant violations are found. Otherwise, posting effectiveness to control extreme bridge loads introduces large uncertainties which reduces such reliability.

5.3 Legal Load Limits and Enforcement

The consequences to bridge safety of overloaded vehicles is well recognized. Large safety factors to cover this situation are uneconomic and may justify pressure by some commercial associations to press for higher legal loads. Instead, designers used strategies with hidden strength margins to cover load growth such as conservative analysis. With improved calculation models, these safety margins have been eroded and hence overloads utilize more of the available strength margin. This fact, combined with longer than anticipated bridge lives implys that stricter load enforcement is necessary. This requires political desire and an efficient technology. WIM displays output in real-time and is available in assisting enforcement to sort vehicles for subsequent portable scale weighing and ticketing. Enforcement is gaining political support as the public learns of road damage. Widespread load enforcement can extend bridge and pavement lives.

5.4 Rating and Permit Assessments

Rating and permit checks compare specified loads and allowable stresses. The latter are often increased above original design levels to reflect better control or less uncertainty in some of the behavior variables. The recent Ontario Code reflected the relative uncertainties in assessment compared to design [9]. Different limit state safety factors are used in assessment. To generalize such safety developments the following aspects should be included:

1) Exposure period. The load factors model load uncertainties and probability distributions of extreme occurrences. This distribution is a function of inspection interval, so shorter periods may have lower expected maximum loads.

2) The optimum reliability targets can be lower for assessment than design because of the trade-off between costs and risk present in such decisions. For new construction, the marginal costs to increase strength, and hence reliability, are much smaller than for an existing structure when strengthing is required.

3) A history of a particular bridge's acceptable performance reduces its modelling uncertainties. These required higher safety factors for new construcrion. Uncertainties include analysis, dimensional tolerances, fabrications and construction factors; in addition, if some simple strain or deflection measurements are made to rationalize the predicted behavior. This factor is recognized for example, in concrete bridges or foundations in which lack

of visual distress signs usually prevents posting in spite of assessment calculations.

4) Field observation of loading spectra at the site also justifies changes in assessment safety factors. New designs are dependent on (vague) forecasting of possible future load patterns. For the period between inspections, such extrapolations are unnecessary.

5) Material uncertainties normally increase with older bridges due to possible corrosion and fatigue weakness. On the other hand, the economic penalties of limiting permit vehicles or reducing capacity suggest that total structure system analysis and reliability be employed to justify increased capacity. For example, to recognize load redistribution. Nonlinear analysis verified by tests have shown significant reserve strength for bridges with adequate redundancy or parallel load paths. The cost of such analyses or testing is justified if it eliminates public inconvenience or costly unnecessary strengthening.

These items are merely an outline of the complex factors in assessing existing bridge structures. The cost, however, in these decisions are often major and hence, it is worth considering new approaches.

6. CONCLUSIONS

1) The decision process for rating, posting, strengthening or replacing existing bridges can be considerably more involved than designing new structures. This activity warrants further research including data on existing loads and predictions of total system performance.

2) Reliability analysis of fatigue spectra and extreme loads may broaden the scope for decision-making and provide a better measure for allocating critical resources. Component safety checks and associated partial factors for assessment should be separated from design safety factors in new construction. Some work exists but further development should incorporate ultimate strength capacities and system reliability models when redundant load paths can be verified by analysis or field testing.

3) New Weigh-In-Motion technology is available to provide better information on bridge loading spectra. For bridge assessment, the data gives appropriate site loading statistics. Bridge measurements in conjunction with weigh-in-motion can verify analyses assumptions, check dynamic response and determine stress distributions at critical fatigue-sensitive locations. This data may ultimately be incorporated in a reliability model for comparing alternative strategies and evaluating priorities for resource allocation.

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