Zeitschrift: IABSE reports = Rapports AIPC = IVBH Berichte
Band: 60 (1990)

Artikel: Inelastic bridge rating for steel beam and girder bridges
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DOI: https://doi.org/10.5169/seals-46515

Inelastic Bridge Rating for Steel Beam and Girder Bridges

Evaluation inélastique de ponts à poutres d'acier

Inelastische Auswertung von Stahl Balkenbrücken

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SUMMARY

This paper outlines the results of a study aimed at utilizing some of the inelastic reserve capacity for regular periodic rating of beam and girder bridges. Two methods are presented: one applies to multi-beam bridges with compact sections, while the other method can also be used to rate non-compact plate-girder bridges. The factored live loads will produce moderate inelastic deformations at the limit state.

RÉSUMÉ

Cet article présente les résultats d'une étude visant à profiter de la surcapacité inélastique en vue de l'évaluation périodique routinière de ponts d'acier composés de profilés laminés ou de poutres assemblées. Deux méthodes sont exposées. La première concerne les ponts à poutres multiples à sections laminées compactes. La seconde peut aussi évaluer des ponts à poutres assemblées à sections non compactes. Les surcharges pondérées produiront des déformations inélastiques modérées à l'état limite.

ZUSAMMENFASSUNG

Die Ergebnisse einer Forschung über die mögliche Ausnutzung der inelastischen Reserve von Balkenbrücken während der periodischen Bewertung werden hier zusammengefasst. Zwei Methoden werden beschrieben: eine davon gilt für Balkensysteme mit kompakten Querschnitten, die andere erfasst auch nicht-kompakte Balken. Die faktorisierten Nutzlasten bewirken nur kleine, fast unmerkliche Dauerverformungen.

1. INTRODUCTION

Many older steel beam and girder bridges have been judged to be structurally deficient based on rating methods using conservative elastic analysis techniques and current design procedures[1]. However, slab-on-steel girder bridges are highly redundant structures and show, like most steel structures, a significant redistribution of moments and a large reserve capacity in the post-elastic range. To more realistically asses the capacity of a bridge, this reserve strength should be considered. This paper summarizes development of an inelastic bridge rating procedure which considers this reserve capacity.

Two ultimate limit states are presented: (1) the shakedown limit of compact bridge systems and (2) residual damage deflection limits. The techniques are applicable to simple and continuous, straight steel beam and girder bridges.

2. SHAKEDOWN LIMIT STATE OF BRIDGE SYSTEMS[2]

The shakedown limit is defined as the maximum load cyclically applied to the system for which deflections stabilize. The two major developments for the shakedown limit state models are (1) a direct method to find the global shakedown limit load of a bridge system and (2) inelastic models to analyze bridge systems in the post-elastic range. The global shakedown limit method is derived from the shakedown theorem, the bridge deck system behavior, and global equilibrium equations. The method involves condensing the system responses and strengths into a global kinematic incremental collapse mechanism. The grillage analogy is used for the elastic and inelastic analyses. The shakedown upper bound mechanism method can be employed to find the critical shakedown limit state for an assumed global incremental mechanism shown in Figure 1:

$$\Gamma\sum_i (M_{el}^+)_i\theta_i+\Gamma\sum_j (M_{el}^-)_j\theta_j+\sum_i (M_d^+)_i\theta_i+\sum_j (M_d^-)_j\theta_j = \sum_{i,j} (M_p)_{i,j}\theta_{i,j}$$

where:

Γ = shakedown load factor

$(M_{el})_{i,j}$ = maximum positive or negative girder moment at section i or j from an èlastic analysis of the grillage

$(M_d)_{i,j}$ = dead load moment at section i or j

$\theta_{i,j}$ = global kinematic mechanism rotation at section i or j

$(M_p)_{i,j}$ = member capacity at section i or j

i,j = section with rotation in the kinematic collapse mechanism

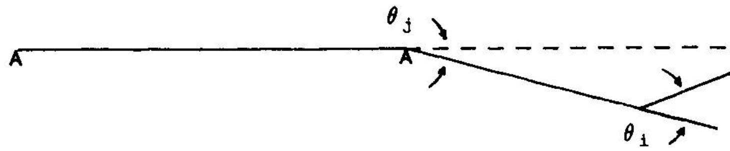

Figure 1 Global Incremental Collapse Mechanism

The result is that the bridge system can be reduced to an equivalent single girder analysis where the elastic moment envelope is the summation of all the individual grillage girder elastic moment envelopes across the global section. Likewise, the dead load moments and moment capacities of the equivalent single girder are the respective sums of the individual girder values.

The models were used to rate three noncomposite, compact one- (13.7m), two- (16.8,16.8m), and three-span (16.8,19.8,16.8m) bridges. All had five W27X102 (US) girders spaced at 2.1m with a 180mm concrete deck. The loading consisted of the critical of the standard factored AASHTO[3] rating vehicles. Four limits were investigated: the current AASHTO method[3] using lateral distribution factors and a first hinge limit, first hinge of the system, shakedown of the system, and the system collapse limit.

Limit State Type	AASHTO Method	Grid 1st Hinge	Grid Shakedown	Grid Collapse
Single-Span	0.961	1.042	1.124	1.529
Two-Span	0.944	1.013	1.127	1.631
Three-Span	0.957	1.027	1.125	1.631
Avg Incr. over AASHTO Method	-	7.7%	18.0%	67.4%
Avg Incr. over Grid 1st Hinge	-	-	9.6%	45.5%

Table 1 Example Bridge Rating Factors

Table 1 presents the results. The shakedown limit state showed an average of 18.0% reserve capacity over that of AASHTO and 9.6% reserve capacity over that of the first hinge of the grid system. This inelastic reserve capacity is ignored in the current ultimate first hinge formation limit states. The average shakedown limit load, however, is only 70.4% of the collapse limit load. Figure 2 shows the effect on structural behavior when a load of 1% over shakedown is applied to the two-span example bridge. The bridge exhibits incremental collapse (non-stabilizing deflections). Incremental damage occurs at a rate so as to render the bridge useless after relatively few cycles. Therefore, it is reasonable to assume the shakedown load as the ultimate limit state. Shakedown better represents the ultimate strength of the bridge and still ensures an adequate margin of safety against incremental collapse.

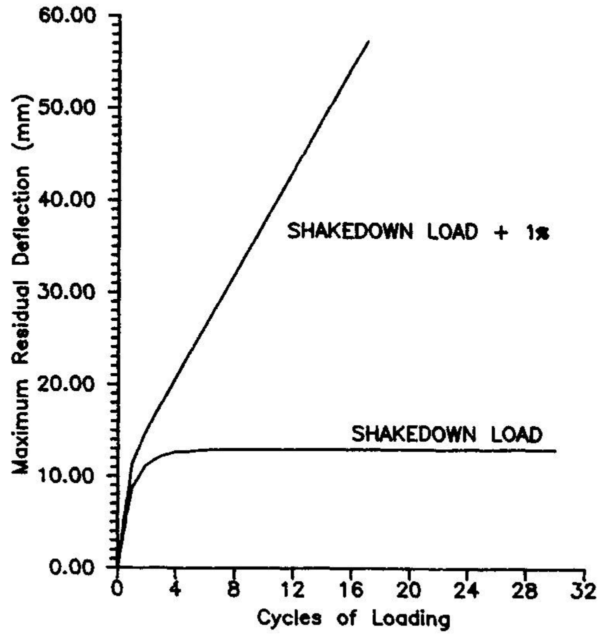

Figure 2 Residual Deflection

3. RESIDUAL DAMAGE DEFLECTION LIMITS[4]

Residual Damage Analysis (RDA) provides a new way of rating against an inelastic deflection limit state, defined as the ratio of the span to midspan inelastic deflection, or C = L/D. RDA utilizes the conjugate beam method beyond the elastic range and into the inelastic range of the structural load-deformation response. The moment-rotation model developed for RDA is based on the results of recent research into the inelastic behavior of steel composite and non-composite girders[5,6].

Current elastic bridge rating methods [1,3] restrict factored truck loads to the maximum level at which all load-induced deflections will vanish once the load is removed, i.e., the elastic load limit. Using RDA, more liberal load allowances can be achieved by allowing a modest amount of permanent deflection to remain after the factored loads are removed. Because load factors are used, we are assured that we will seldom, if ever, actually realize this residual damage. While AASHTO contains an inelastic steel bridge design method known as Autostress Design [5], it currently provides no inelastic rating method. RDA was developed to meet this need.

Residual Damage Analysis performs a single girder analysis of a bridge subjected to moving truck loads. Where inelastic rotations may form, the moment versus inelastic rotation, M-θi, relationship shown in Figure 3 is invoked to solve for the additional unknown on the conjugate beam - the inelastic rotation, θi.

A computer program was developed to accommodate the case of multiple hinges forming as the result of the moving rating truck load. In this situation, the interplay between increments of inelastic rotation and their associated residual moment field must be allowed to run its course with multiple truck passes, i.e., the bridge must be allowed to shake down. When only one inelastic hinge rotation occurs, RDA can be used to manually rate a steel girder bridge, because, in this instance, shakedown occurs with a single pass of the load.

When manually rating against a specific level of residual damage, defined as the ratio of the length of span to the midspan permanent deflection, C=L/D, the following steps are followed:

1) Determine the required value of inelastic rotation, θi, to achieve the inelastic deflection limit, C=L/D. With this value of θi, determine the accompanying residual moment, Mr. (This relationship is easily obtained using the conjugate beam "loaded" with the inelastic rotation "force," θi.

2) Determine the parameters necessary to define the moment versus inelastic rotation, M-θi, model.

3) Determine the dead load moments, Md, and the live load elastic moment envelope, Ml.

4) Equate θi of Step 1 with the expression obtained in Step 2. Solve for the hinge resisting moment, Mi.

5) Determine the inelastic rating factor, IRF, by applying the following formula at the hinge point:

$$(IRF) * Ml + Md + Mr = Mi$$

Figure 3 shows a symmetrical two-span (L=18.3m), noncomposite bridge girder subjected to a moving HS-20 truck and a uniform load

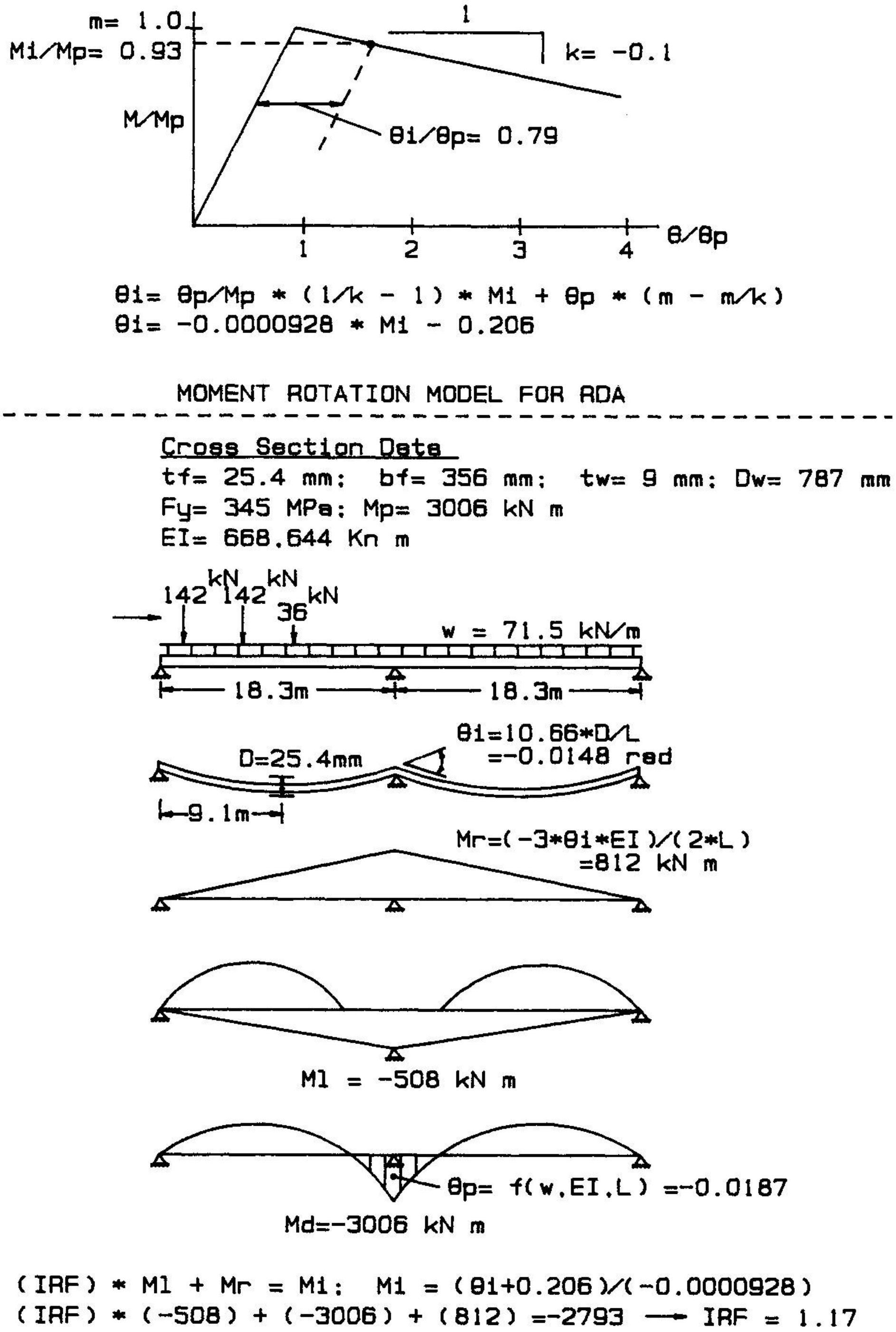

Figure 3 Example of Manual Rating Using RDA

which causes the elastic bending limit, Mp, to be reached at the interior support. For purposes of clarity, the load and resistance rating factors are taken as unity. The inelastic load rating factor, IRF, is to be computed for an inelastic midspan deflection limit of 25.4mm (C=L/D=720) due to an inelastic hinge rotation at the interior support.

Based on an elastic load limit, the elastic rating factor applied to the concentrated load would be RF=0 (dead load alone is the elastic limit). However, an inelastic rating factor of IRF=1.17 is realized by allowing the 25.4mm of residual damage. This represents an overall load increase of (1.17*320)/(36.6*71.5), or 14% above the elastic limit.

4. SUMMARY

Many of the bridges classified as deficient using current methods may be reclassified as sufficient if a true representation of the ultimate strength were considered. The incorporation of the post-elastic strength of redundant structures is more rational than the current elastic limits and the system shakedown limit state or deflection limit is a more meaningful ultimate limit state for bridge rating. The new procedures, with appropriate load and resistance factors, ensure an adequate margin of safety, while utilizing the inelastic reserve capacity of the bridge structure.

ACKNOWLEDGEMENT

This research was sponsored under the auspices of the National Cooperative Highway Research Program (NCHRP 12-28(12)). The findings and conclusions herein are those of the authors and do not necessarily reflect the views of the sponsors.

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