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Load rating of bridges - current practices and issues

Umarani Gunasekaran, Kanchanadevi Ashokkumar,
Rose Enid Teresa Amaladosson
Department of Civil Engineering, Anna University, Chennai, India
e-mail: umaraniguna@yahoo.com

The most common approach to assess the safety of a bridge is load rating. Load rating of bridges is an important task that needs more attention and to be exercised with care. A prior knowledge base is highly essential in performing such a forbidden task. In this paper load rating practices carried out globally is reviewed with special emphasis on fatigue effect. The behaviour of members and materials under fatigue loading, various models proposed to simulate fatigue loading are highlighted.

Keywords: Bridges, load rating, fatigue, issues, practices.

Introduction

Bridges are not simply structures made out of materials, they are part of life. In many places life would be seriously disrupted, traffic would be paralyzed and business would be terribly affected if the bridges fail functioning. Hence the assessment of bridges periodically for its performance turns out to be an important task.

The assessment of bridges could be done by conducting load test, correlating the bridge under study with the bridge whose details are known and analytical load rating. Performing the load test is a forbidden task as it involves a huge deal of men and material. The analytical rating of bridges is comparatively easy to perform but the reliability of the results highly depend upon the assumptions made with regard to loading, load positioning, long-term effects produced, limitation of structural analysis to model the actual scenario, material behaviour etc.

Thus the effectiveness of the system depends upon the ability of the system to simulate the problem. Hence the knowledge of practices adopted and the issues involved are found to be much inevitable.

Load rating becomes essential under following circumstances:

- the design live load is less than that of the heaviest statutory commercial vehicle plying or likely to ply on the bridge;
- exact live load for which the bridges are designed is unknown;
- tackling today's increased traffic demand;
- regulating with adverse environmental effects;
- catering for the material ageing;
- indication of distress leading to doubt about structural and functional adequacy.

Review of global practice

Most of the countries in the world do not have any comprehensive bridge rating system. In many countries, load rating of bridges is carried out in connection with passage of exceptional loads only. The national loading standards, bridge codes and standards vary to a large extent for all these countries and so also the systems followed. Load rating includes the concept of "inventory" and "operational" rating. Inventory rating is the capacity rating for the vehicle type used in the rating that will result in a load level which can safely utilize an existing structure for an indefinite period of time. Inventory load level approximates the design load level for normal service conditions. Operating rating will result in the absolute maximum permissible load level to which the structure may be subjected for the vehicle type used in the rating. This rating determines the capacity of the bridge for occasional use. Allowing unlimited numbers of vehicles to subject the bridge to the operating level will compromise the life of bridge. This value is typically used when overweight permit vehicle moves. The posting rating is the capacity rating for the vehicle type used in the rating that will result in a load level which may safely utilize an existing structure on a routine basis for a limited period of time. The posting rating for a bridge is based on inventory level plus a fraction of the difference between inventory and operating.

Loads

The loads used by various countries for rating purposes, are of three types: (i) design live loads at the time of construction; (ii) presently allowed legal loads; and (iii) specific loads for rating purposes only. Some of the loads in category (iii) are military loads and not much information is available on them. Most countries use presently allowable legal loads or design loads at the time of construction (IRC SP-37, 1991).

Stresses

The stresses used in the rating schemes also vary a great deal. Some countries use the allowable design stress in effect at the time of construction, whereas others allow larger than design stresses for rating purposes, allowing as much as 75 percent of the yield stress in steel. In several countries stresses for rating of older bridges are reduced, leaving the allowable stresses upto the judgment of the rating engineer depending on the condition of bridge. There are also other variations viz. reduction in impact factor, which underscores the necessity of speed control of heavy commercial traffic on the bridge.

Fatigue

Most countries do not rate bridges for fatigue loading and leave this to the discretion of the rating engineer. Fatigue is generally relevant for steel bridges. Some recent research works in steel bridges are by Righiniotis et al. (2007) and Caglayan et al. (2008). However, the subject of fatigue behaviour of concrete bridges subjected to heavy repetitive loading (e.g. railways) is still under research. AASHTO has given new Guide Manual for Condition Evaluation and Load and Resistance Factor Rating of Highway Bridges in March 2000 under a National Cooperative Highway Research Program research project and adopted as a Guide Manual by the AASHTO Subcommittee on Bridges and Structures at the 2002 AASHTO Bridge Conference (Minervino et al., 2004). This Manual is consistent with the LRFD (Load and Resistance Factor Design) specifications in using reliability based limit states philosophy and extends the provisions of the LRFD specifications to the areas of inspection, load rating, posting and permit rules, fatigue evaluation, and load testing of existing bridges. In the current AASHTO LRFD specifications, the fatigue design considers only one design truck per bridge with 15% dynamic allowance. While this empirical approach may be practical for regular short and medium span bridges, it may not be rational for long-span bridges that may carry many heavy trucks simultaneously (Chen and Cai, 2007). The new LRFR (Load Resistance Factor Rating) Manual has implemented a systematic and more flexible approach to bridge load rating that is reliability based and provides a more realistic assessment of the safe load capacity of existing bridges. In Germany, fatigue is considered on bridges with mixed highway and railway loadings. In Sweden, for very important structures, a detailed fatigue life calculation is made.

Design philosophy

Most countries use working stress methods for the rating calculations. But some of them, especially for modern bridges, are using limit state methods in conjunction with the working stress methods. In USA Load factor method of design is adopted for rating as outlined in AASHTO Manual for Condition Evaluation of Bridges.

Computer programme

USA and Denmark have specific computer programmes developed for bridge rating but many countries use the design computer programmes for the recalculation of stresses for rating purposes. Ratings are done using Wyoming Department of Transportation's Bridge Rating and Analysis of Structural Systems (BRASS) Girder computer program. Ratings for timber bridges are done by the working stress method using BRASS Girder. When BRASS cannot be used due to geometry, structure type, or material, other computer programs such as STAAD and other advanced techniques such as finite element analysis, AASHTO-ware products, or hand calculations are to be used with approval of the Bridge Management engineer.

Issues unaddressed

The issues unaddressed in most of the bridge codal provisions are (i) Fatigue effect of loading (ii) Creep and shrinkage of reinforced cement concrete (iii) Deterioration condition (iv) Development of the deterioration and its influence on structural stress strain response (v) Environmental effects (vi) Damages due to accident (vii) Traffic load and demand. Out of the above issues a detailed review on effect of fatigue and the methods to incorporate fatigue in load rating is discussed.

Theories and approaches for fatigue damage

The researches on fatigue damages focus on two aspects; one is the theoretical research on the behaviour of fatigue damage and its constitutive modeling, such as the approaches based on crack growth concepts (Miller and Zachariah, 1977; Miller, 1985) and (Lin and

Smith, 1999), the continuous damage mechanics (CDM) models (Shang and Yao, 1999; Chaboche and Lesne, 1988; Lemaitre and Plumtree, 1979) and the energy-based theories (Golos and Ellyin, 1987; Halford, 1966), etc. These fatigue models have advantages in describing the deterioration on accumulative fatigue process. However they are still on a primary stage to investigate the material specimens in the laboratory and have a long way to go for engineering applications. The second is the research on fatigue analysis method for engineering structures. In this aspect, bridge fatigue behaviours and available approach for evaluating fatigue are studied. Systematical works have been carried out by National Cooperative Highway Research Program (NCHRP) such as Schilling (1978), Fisher (1980; 1983) and Moses and Schilling (1986), in which fatigue behaviour of welded steel bridges under variable-amplitude loading was experimentally investigated for different bridge members and different class of weld details. These experimental results are applied to develop the current specifications of bridge fatigue in which S-N curves for components and details grouped into several categories are given according to their fatigue resistance. The Miner's law method used in these guides has the advantages of simplicity combined with mathematical elegance, making them attractive to practicing structural engineers.

Fatigue behaviour of reinforced concrete

Concrete under fatigue loading

Plain concrete under force-controlled compression or tension fatigue loading exhibits strongly increasing strains within a short interval of its life (Cornelissen and Reinhardt, 1982; Dyduch et al., 1994) followed by a period of steady phase, with slight increasing strains. At the end, strains again increase significantly before the specimen fails. The modulus of elasticity decreases significantly during the test, mainly due to crack formation at the microscopic level. Under uniaxial compression, the concrete-matrix is extensively micro-cracked at the last period. An increasing number of cracks appear parallel to the loading direction on the outer surface of the specimen with subsequent failure.

Concrete behaviour under tension fatigue loading is also dominated by crack propagation; early age micro-cracks in the cement matrix and at the interface between aggregates and the cement matrix propagates steadily and perpendicular to the loading direction until the specimen fractures showing one discrete crack. Concrete subjected to stress reversal deteriorates rapidly which is explained by the interaction of the differently oriented micro-cracks due to compression and tension loading (Cornelissen and Reinhardt, 1982). There is no test under pure shear fatigue loading because it is difficult to apply this type of loading without creating other stresses.

Steel reinforcement under fatigue loading

The fatigue life of steel reinforcement can be divided into a crack initiation phase, a steady crack propagation phase and brittle fracture of remaining section. Crack initiation on a ribbed high yield steel bar usually starts at the root of a rib, which causes stress concentration. Welds, the curvature of bent bars and corrosion favour crack initiation and lead to low fatigue strength.

Reinforced concrete elements under fatigue loading

Bending

Fatigue loading causes progressive deterioration of the bond between reinforcement and concrete. Large crack widths and a smaller contribution of concrete in tension between the cracks result in larger deflection. Failure normally occurs due to rebar fatigue fracture; another failure mechanism is) fail due to reinforcement fracture when subjected to spalling of concrete in the compression zone. However, even over-reinforced beams (i.e. concrete compression failure under static loading fatigue loading.

Shear

Beams without shear reinforcement develop a shear crack pattern after the first few cycles; deformation increases only slightly. A critical shear crack appears which crosses the bending cracks. The large width of the cracks does not allow any stress transfer and as a result, the beam fails due to fatigue of compression strut (upper flange); beams with shear reinforcement show fatigue of stirrups or spalling of surrounding concrete ; failure is ductile. Failure tests of scaled deck slabs have shown a punching shear failure mode; moving wheel loads leading to stress reversals are more detrimental to fatigue strength than stationary pulsating loads (Perdikaris.and Beim, 1988; Sonada and Horikawa, 1982).

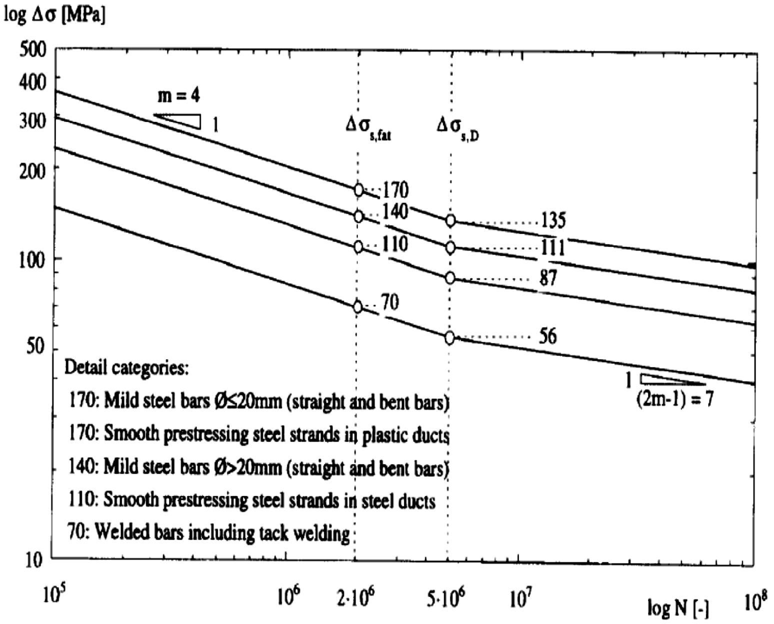
Fatigue models - S-N approach

The first approach to fatigue assessment is based on stress S versus number of load cycles N curves (S-N curves). Fatigue resistance is determined by testing, and fatigue reliability of a structural element over its design service is verified if the fatigue resistance R fat is larger than the effect of fatigue loading S fat. The fatigue safety values of steel reinforcement and concrete are determined separately. For steel reinforcement the relevant parameters are (1) the stress ranges; (2) the number of load cycles and (3) discontinuities both in the cross section and layout of the steel reinforcement resulting in stress concentration at possible fatigue damage location.

Test results are plotted using double-logarithmic scale and, usually, a 5% fractile-criteria is used to determine the slope of S-N curve and the detail category defined as the fatigue strength at $2x10^6$ load cycles. A correction factor is introduced to account for the cumulative fatigue damage caused by the stress spectrum of traffic models for a lifetime of 100 years. This correction factor, as calculated for the steel bridge using the Palmgren-Miner damage accumulation rule, is also applicable with sufficient accuracy to steel reinforcement in concrete bridge (Chart 1).

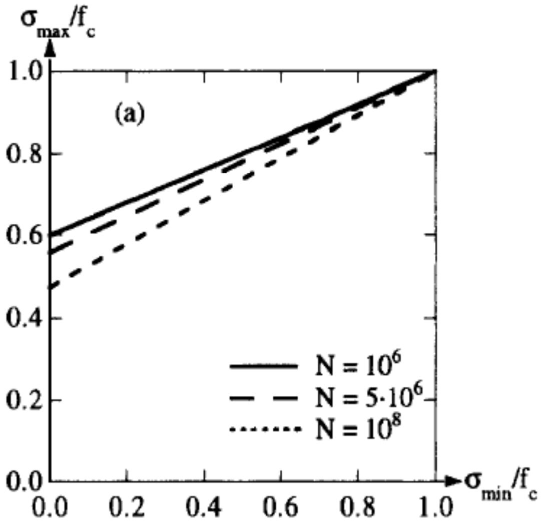
Fatigue of concrete is in principle defined by a pair of stresses i.e. the maximum and minimum stress values as most important fatigue relevant parameter for both normal and shear stresses. The effect of this pair of stresses on the fatigue strength as a function of number of load cycles is best represented by Goodman diagram (Charts 2 and 3). In the case of stress reversals fatigue resistance is significantly reduced. Stress reversals occur in the deck slab due to the passage of a moving load.

FIGURE 1. FATIGUE STRENGTH OF STEEL REINFORCEMENT



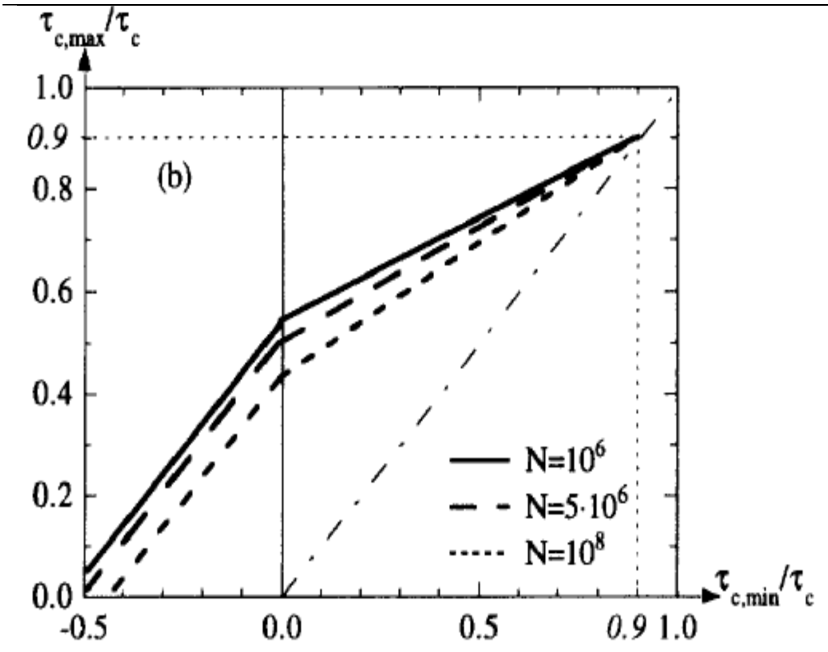
Source: SIA Documentation 0133, 1997.

FIGURE 2. FATIGUE STRENGTH OF CONCRETE AS REPRESENTED BY GOODMAN DIAGRAM FOR COMPRESSIVE STRESSES



Source: SIA Documentation 0133, 1997.

FIGURE 3. FATIGUE STRENGTH OF CONCRETE AS REPRESENTED BY GOODMAN DIAGRAM FOR SHEAR STRESSES



Source: SIA Documentation 0133, 1997.

Other fatigue relevant parameter include the concrete strength and structural size effect which are taken into account by the nominal design values f_c and τ_c for static compressive and shear strength, respectively. The fatigue action effect in the concrete is described by the maximum and minimum stress values due fatigue loading and dead load of the structure including permanent loads. No correction factor is introduced because of a lack of proven models for fatigue damage accumulation in concrete.

Damage accumulation

Damage accumulation models enable the degree of damage due to varying stresses to be determined. The most common hypothesis is the linear damage accumulation by Palmgren-Miner. It describes the sum of damage due to each of the individual cycles and based on S-N curves. This hypothesis has been applied in several investigations. According to Holmen the Palmgren-Miner hypothesis under estimates damage for variable amplitude loading; the values of minimum stress and small amplitude have influence on damage. Cornelissen and Reinhardt report that the hypothesis is conservative with large scatter when based on S-N curves.

Load rating with fatigue

The rating model proposed in (Mohammadi and Polepeddi, 2000) incorporates the fatigue damaging effects of overloads. This is achieved by introducing a "fatigue index" in the rating equation. The index, which appears in the form of a correction factor in the rating equation, is intended as a means to reduce the rating value computed for a bridge in cases where the damage from overloads is expected to be significant. The use of this index by itself does not impose any upper limit on the total number of overloads that may annually be permitted on a bridge. The computation of fatigue damage resulting from overloads is based on Miner's damage accumulation rule and utilizes the stress range, number of cycles (S-N) relation to compute the annual fatigue damage occurring to a bridge component. The S-N relation is defined as

$$N = C/S^m , \qquad (1)$$

where N = number of cycles to failure for the stress range S; and C and m are constants. The constants C and m for structural details are reported by (Munse et al., 1983). For beams with welded cover plates $C = 4.21 \times 10^9$ with m = 3.256. The damage equation is

$$D = n_1/N_1 + n_2/N_2 + \ldots + n_k/N_k , \qquad (2)$$

where D = total damage accumulated in the component. To compute D, the stress population for a given bridge is divided into k ranges. For each range, the stress value S_i is used in (1) to compute the corresponding number of cycles N_i that will cause the failure for S_i. The recorded number of cycles n_i for the S_i stress is then divided by N_i to compute the portion of the total damage caused by S_i. The damage associated with all k stress ranges is then computed using Equation (2).

Bridge rating with consideration for fatigue damaging effect of overloads

The underlying equation in the current practice (AASHTO 1994) of the highway bridge rating is

$$RF = \frac{R-D}{L\,(1+I)} , \qquad (3)$$

where RF = rating factor; R = component resistance (bending, shear, etc.); D and L = dead load and live load effects corresponding to R, respectively; and I = dynamic allowance (impact) factor. Bridge engineers permitting overloads often are interested in establishing the bridge maximum allowable capacity rather than trying to rate every overload.

$$L\,(I+1)_{capacity} = R - D , \qquad (4)$$

Thus using (3) with RF = 1 will result in the maximum capacity in the form of Equation (4). Equations (3) and (4) are the basis for rating. Variations to these equations are provided in the AASHTO code specific to, and to account for such factors as, the type of bridge under consideration, use of load factors, service conditions, limit-state conditions, etc. A factor m_{FLE} is introduced in the denominator of (3) to account for the significance of an overload on the fatigue damage occurring in the components. Based on the investigation on the fatigue damage potential of overloads in the five bridges investigated, it was concluded that such a factor should result in smaller values of *RF* in accordance with the severity of the overloads. Using the m_{FLE} index allows for a built-in mechanism to limit the number of overloads, especially for bridges with marginal structural safety conditions under the application of heavy truck loads. In light of this concept, and in compliance with the LRFD approach, the following rating equation is proposed.

$$RF=\frac{\phi R_n - \sum_{i=1}^{n_D}(\gamma_{Di} D_i) - \sum_{i=1}^{n_L}(\gamma_{Li} L_i)}{\gamma_R L_R (1-I)(1+m_{FLE})} , \qquad (5)$$

where *RF* = capacity reduction factor; R_n = nominal capacity corresponding to the type of load for which the rating is being conducted (e.g., bending moment, shear, etc.); n_D = number of dead load comparisons; n_L = number of live loads other than the rating vehicle; γ_{Di} = dead load factor in the i_{th} dead load; γ_{Li} = live load factor for the i_{th} live load other than the rating vehicle; γ_R = live load factor for the rating vehicle; L_R = nominal live load effect for the rating vehicle; and m_{FLE} = factor to account for the significance of the overload to *FLE*.

Finite element modelling for fatigue stress analysis

The FEM is recommended by the British standards (BSI, BS5400: Part 10) as a rigorous method for structural fatigue stress analysis. The studies by (Nowack and Schulz, 1996) and (Putchkov, 1995) show that FEM has become a highly valuable tool as a basis for evaluation of fatigue behaviour. The work by (Lin and Smith, 1999) describes the finite element (FE) modelling of fatigue crack growth of surface cracked plates, and provides an accurate evaluation of the fatigue life of the structures. However, it is very complicated to establish a FE model of a large practical structure for fatigue damage analysis.

Conclusion

In this paper various load rating systems of bridges is reviewed. The behaviour of members and materials under fatigue loading, various models proposed to simulate fatigue loading are highlighted. Fatigue damage from traffic overloads can become significant if no limits on the total number of overload permits is imposed on a bridge.

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