Analysis and Evaluation of Bridge Behavior Under Static Load Testing Leading to Better Design and Judgment Criteria

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Load testing offers an effective means of investigating the actual behavior of a bridge and detecting a possible abnormal response. A computerized data base of the results of over 200 load tests performed in Switzerland was established to study the behavior of bridges subjected to a load test. This large number of bridges enabled the Institute of Reinforced and Prestressed Concrete of the Swiss Federal Institute of Technology in Lausanne to carry out a comparative statistical study to better understand the behavior of different types of bridges. The main evaluation criteria are the agreement between the measured and calculated deflections and the similarity between the measured and calculated deflected shapes. Although the deflections under loading can be measured precisely, their calculations are difficult because of phenomena usually not taken into account in the design. Statistical analysis of the data base, combined with an analysis of 88 bridges, led to recognition of the contribution to the overall stiffness of nonstructural elements such as reinforced-concrete parapets, asphalt wearing surfaces, and reinforcement. The precise determination of the modulus of elasticity of concrete led to the use of ultrasonic measurements, drilled cores, and molded samples of concrete. The analysis confirmed the correlation between unsatisfactory short-term behavior during the load test and abnormal long-term behavior. Bridges with a low level of prestressing often exhibit unsatisfactory behavior, whereas a higher prestressing level seems to prevent abnormal bridge behavior.

Load testing offers an effective means of obtaining a realistic picture of a bridge's response. The results of a load test permit the verification of the serviceability of the bridge and a check on the design calculations. The load test also serves as an essential starting point for monitoring operations. As will be shown, there is a strong correlation between the behavior of the bridge under a load test and its long-term behavior.

The majority of load tests performed in Switzerland are proof tests carried out before the bridge is put in service. Swiss codes recommend a load test for any new bridge with spans exceeding 20 m (*1*). Since 1973, the Institute of Reinforced and Prestressed Concrete (IBAP) has carried out 210 load tests. The results of these tests, characterizing the static and dynamic behavior of the bridges along with their geometry, were collected in a computerized data base.

Load tests are conducted to determine and quantify the global behavior of a bridge under loading. The load test checks the serviceability of the bridge and identifies the potential risks of cracking and excessive deflections over the lifetime of the bridge. This is done by studying

- The agreement between the measured and calculated deformations,
- The presence of cracks and how much they open under loading, and
- The magnitude of irreversible or permanent deformations due to the test load.

During the load test, bridges are normally loaded to 80 to 100 percent of the unfactored design load (1.0 DL + 1.0 LL). This level is effective, as it leads to substantial deflections while usually not inducing a large amount of cracking in post-tensioned structures. The proof load on the bridge generally consists of three-axle trucks with an individual weight of 250 kN. The trucks are placed symmetrically with their cumulative center of gravity at midspan (Figure 1). Various other loading patterns are used to test bridge bending, torsion, continuity over the supports, and behavior of side spans. The spans to be tested and the load cases are determined jointly by the testing agency and the design engineer. After the test spans and load cases have been defined, the theoretical deflections are calculated by the engineer before the bridge test.

The measurement techniques used are dependent on the geometry and location of the bridge. The preferred method is to have the deflection gauge at ground level connected to the superstructure by taut wires. Optical and hydrostatic leveling systems are also employed when access to the ground is prevented by the landscape or the traffic under the bridge. To increase the precision of measurements, all loading cases are repeated three times. Temperature changes typically induce deflections that are not negligible, leading to a drift of the position of the unloaded bridge. To improve accuracy, measurements of the unloaded structure are taken about every 15 min after removal of the trucks. These measurements without load are used to correct the reference position and also help track the evolution of the temperature-induced and other permanent deflections of the bridge. For more details on load testing procedure, see the work by Hassan (*2*) and Markey (*3*).

FIGURE 1 Load test of Daillard bridge in French-speaking Switzerland.

Calculation of Deflections

Calculating the exact deflections of a bridge subjected to a load test is not a trivial task. Factors that are often neglected in the design may significantly influence the stiffness of the bridge. An initial evaluation of the data base showed that approximately one out of five bridges (18.5 percent) had measured deflections that exceeded the calculated values by more than 20 percent. This illustrates the complexity of the problem. The two main sources of error in these calculations are uncertainty as to the modulus of elasticity of the concrete and the increase in the moment of inertia caused by nonstructural elements. The level of loading and the amount of prestressing are also important. To achieve reliable results, the following factors need to be considered:

- The actual modulus of elasticity of concrete;
- The effective moment of inertia of the superstructure, including not only the structural members, but also the parapets, asphalt wearing surface, and reinforcement;
- The level of loading during the test and the presence of cracks (state I or state II);
- The level of post-tensioning or prestressing; and
- The method of construction (incremental launching, balanced cantilever method, precast, or cast-in-place).

These points were identified through statistical analysis of the data base and confirmed by a deterministic analysis (*2,4–7*). Only the main points are presented here.

Modulus of Elasticity

The modulus of elasticity of concrete should be known precisely for all deflection calculations. The formulas given in national codes usually relate the modulus of elasticity to the compressive strength of concrete, which is rather inaccurate (*8*). Ideally, the modulus of elasticity of the concrete should be determined on molded samples taken during bridge construction. The value given by the standardized laboratory test has been found to be very reliable and representative of the concrete of an entire bridge. Unfortunately, these results are often un-

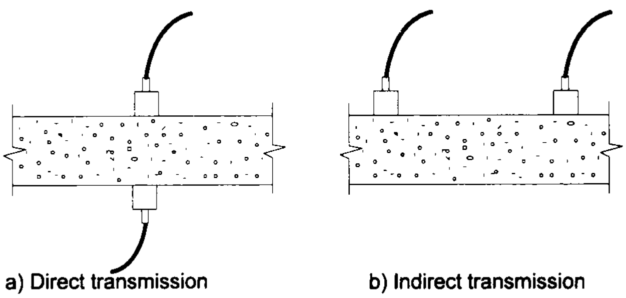

FIGURE 2 Arrangement of transducers for ultrasonic measurements.

available for existing structures. In such cases, ultrasonic measurements offer an efficient method to determine the modulus of elasticity, especially using the direct transmission method (Figure 2).

In the past, this method has often been used to evaluate the compressive strength of concrete. But because there is no physical relationship between the ultrasonic pulse velocity in concrete and concrete strength, this method does not yield accurate results, as illustrated in Figure 3(a), which shows the compressive strength of cores as a function of the measured ultrasonic pulse velocity. However, as Figure 3(b) shows, the dispersion is much smaller for the modulus of elasticity, since there is a direct physical relationship between the speed of sound in a body and the body's modulus of elasticity:

$$E_d = \frac{(1 + \nu)(1 - 2\nu)}{1 - \nu} \gamma v^2 \quad (1)$$

where

E_d = dynamic modulus of elasticity,
γ = density of concrete,
ν = Poisson's ratio, and
v = ultrasonic pulse velocity.

The dynamic modulus of elasticity obtained from the ultrasound pulse velocity can be converted into a static modulus of elasticity. The relationship between the two moduli is empirical and time dependent. Preferably it should be determined experimentally for each geographical area because it depends on the type of aggregate. General formulas giving the modulus of elasticity directly from the ultrasound pulse velocity for all types of concrete and at all times are usually not sufficiently accurate. For the French-speaking part of Switzerland, the following formula (2) gives good results:

$$E_c = kv^2 \quad (2)$$

where

E_c = status modulus of elasticity of concrete (GPa),
v = ultrasonic pulse velocity (km/s), and
k = empirical value (k = 1.68 for $t \geq 180$ days (t in days); $k = t^{0.1}$ for $t < 180$ days).

Effective Moment of Inertia

Analysis of 88 continuous bridges demonstrated significant contributions to the overall stiffness by the parapets, the asphalt wearing surface, and the reinforcement. It

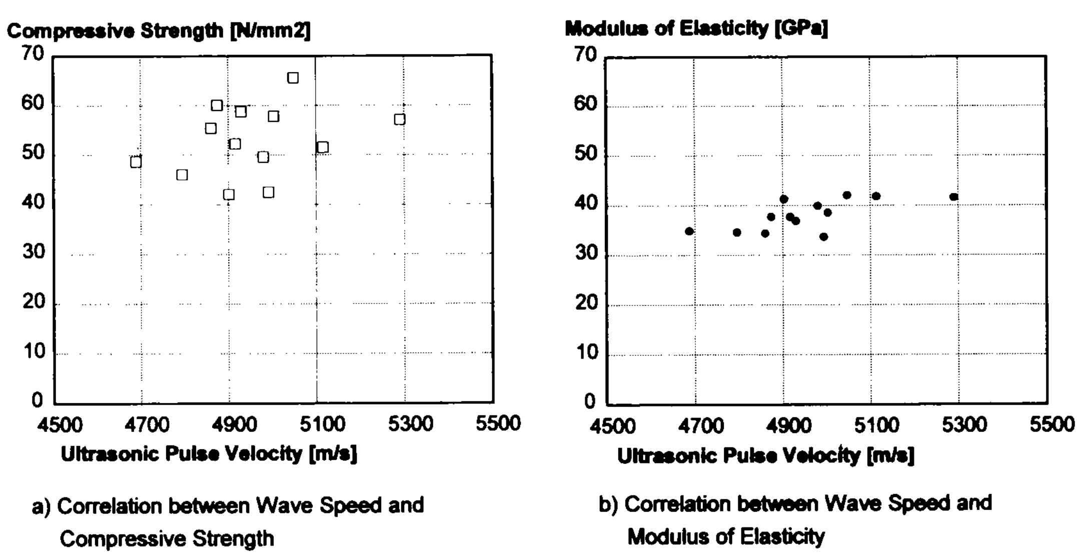

FIGURE 3 Modulus of elasticity and compressive concrete strength versus ultrasonic pulse velocity.

also showed that near the supports, the effective slab width should be taken into account for accurate calculations of deflections.

Parapets

The contribution of parapets to the overall stiffness of the bridge can be significant, sometimes in excess of 20 percent of the stiffness of the structural concrete. Parapets should therefore be taken into account in calculating the effective moment of inertia of the superstructure. Because of some cracking or microcracking caused by shrinkage, thermal stresses, and external loads, the effectiveness of parapets is slightly lower than if they were designed to be a part of the structural concrete. Also, this study was conducted assuming that the concrete used for the parapets is similar to that used for the structural members. While this is not generally the case, it was considered acceptable because the modulus of elasticity of concrete depends more on the aggregates, which remain the same in a given area, than on the cement paste, which is usually tuned for parapets. The lower effectiveness of the parapets can be accounted for by assigning a lower modulus of elasticity to the parapet concrete. In the positive moment region, the modulus of elasticity of the parapets can be taken as 80 percent of that of the structural concrete. Because the parapets are usually cracked over the supports, the modulus of the parapets should be reduced to 40 percent of the modulus of the structural concrete for a length of 15 percent of the span on either side of the supports, as shown in Figure 4. For smaller parapets, like those supporting metal handrails, the modulus of elasticity needs only to be reduced to 90 percent of its design value over the whole length of the bridge. The metal handrails themselves can be ignored. Some bridges had either partly precast or discontinuous cast-in-place parapets. Overall, the increase in stiffness induced by these parapets is of the same magnitude as if they were monolithically cast and continuous.

Asphalt Wearing Surface

The asphalt layer increased the moment of inertia of the superstructure by an average of 6 percent for the 88 bridges analyzed. This contribution, which depends on the temperature of the asphalt at the time of the test, can be calculated as shown in Equation 3 (2), which is valid for the type of asphalt used in the French-speaking Switzerland:

$$E_{\text{asphalt}} = 22 - 0.7T \tag{3}$$

where E_{asphalt} is the modulus of elasticity of the asphalt wearing surface (GPa) and T is temperature (°C).

Figure 5 shows the average increase of inertia of the superstructure produced by 100 mm of asphaltic wearing surface as a function of temperature for 88 bridges of different cross sections. This thickness is typical of current applications in Switzerland.

Reinforcement

The reinforcing steel increases the moment of inertia of the superstructure and should be taken into account in calculating the stiffness (transformed section). This increase varies between 2 and 4 percent depending on the type of cross section and the reinforcement ratio.

Grouted post-tensioning cables also increase the moment of inertia slightly, usually by about 2 to 3 percent. For more accurate calculations, the increase of inertia due to the post-tensioning steel can be expressed for box-girder bridges and multigirder bridges as a function of the load balancing level (defined as the fraction of the dead load that is balanced by post-tensioning (3,9) and the span-to-depth ratio of the superstructure as in the following equation (2):

$$\text{Increase of moment of inertia } [\%] = 0.17\beta\lambda \tag{4}$$

where

$\beta = u/g$ = level of load balancing,
u = deviation force (balancing force) due to cable curvature,

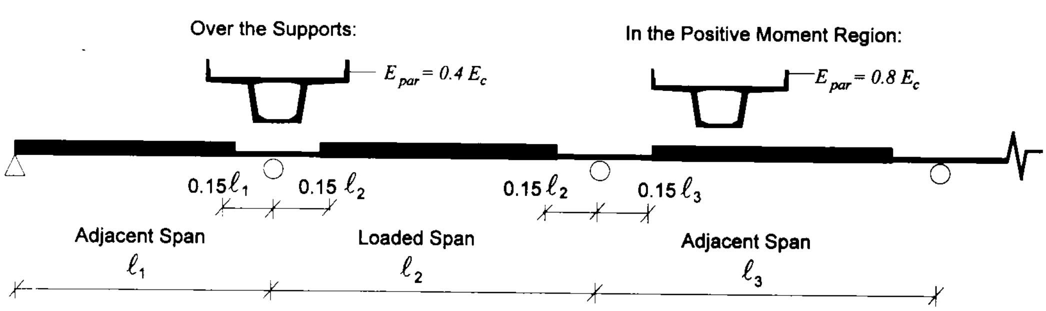

FIGURE 4 Proposed model for taking parapets into account in deflection calculations.

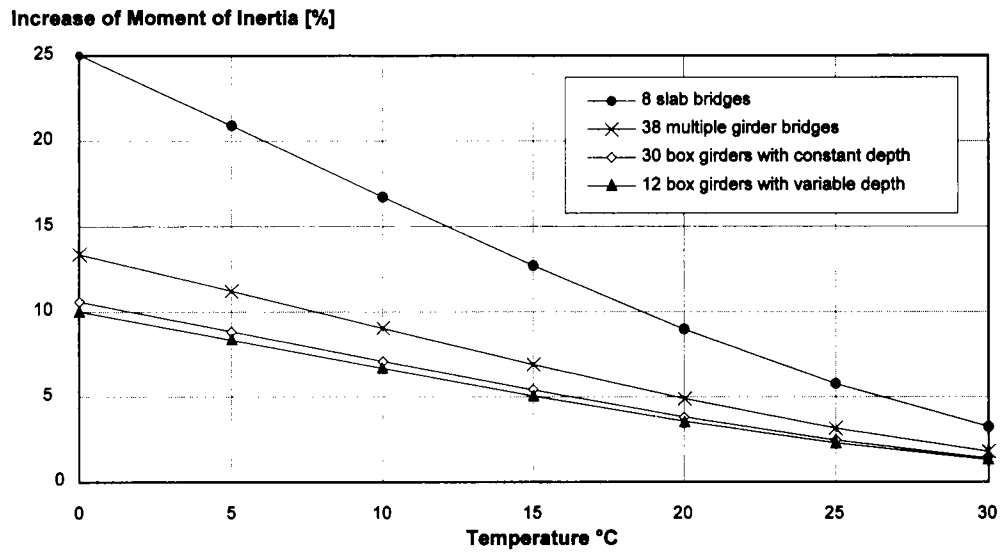

FIGURE 5 Increase in moment of inertia due to 100 mm of asphalt as a function of temperature for 88 bridges of different types.

g = dead weight of the superstructure, and
$\lambda = \ell/h$ = span-to-depth ratio of the structure.

The increase of the moment of inertia of slab bridges due to post-tensioning cables is almost negligible (between 0.5 and 1 percent).

Effective Slab Width

The effective slab width should be used to calculate the effective moment of inertia of the superstructure. It has been shown that the total width of the slab can be taken into account in the span under uniformly distributed loads. Over the supports, however, the full width cannot be used to calculate the effective moment of inertia. The moment of inertia of the cross section at the supports may be reduced by as much as 20 percent because of the effective slab width.

Interpretation of Results

The interpretation of the results of a load test is based on the comparison between the measured and calculated deflections, on the similarity between the measured and calculated deflected shapes, and on the presence of cracks or permanent deformations.

The above approach to calculating the deflections results in improved agreement between the measured and calculated deflections. The remaining differences are caused by cracking because of either a high level of loading during the test or a low level of post-tensioning. Bridges with load test deflections higher than those predicted by calculations typically showed an increase of cracking over time and, in some cases, excessive deflections.

The long-term monitoring of these bridges, along with the detailed analysis below, led to the definition of thresholds beyond which the bridge should be kept under surveillance and inspected more frequently. The proposed thresholds concern two parameters; the first is the difference between the measured and calculated deflection at mid-loaded span, and the second is the lack of similarity, defined as the difference between the ratio of measured to calculated deflections in the loaded span and that in the adjacent spans.

Alarm Threshold of Deflections Divergence

Three limits have been established as thresholds defining satisfactory behavior; they are shown in Figure 6.

Tolerance Threshold

Bridges with a ratio R of measured to calculated deflections exceeding 1.10 are likely to be cracked. These bridges should be examined in more detail by verifying the calculation model and the value of the modulus of elasticity. The tensile stresses should be calculated to check the presence of cracking and a detailed inspection of the bridge should follow. If cracking is observed, the bridge should be inspected more frequently, with special attention paid to the evolution of this cracking. Because of the accuracy of the measurements, the tolerance

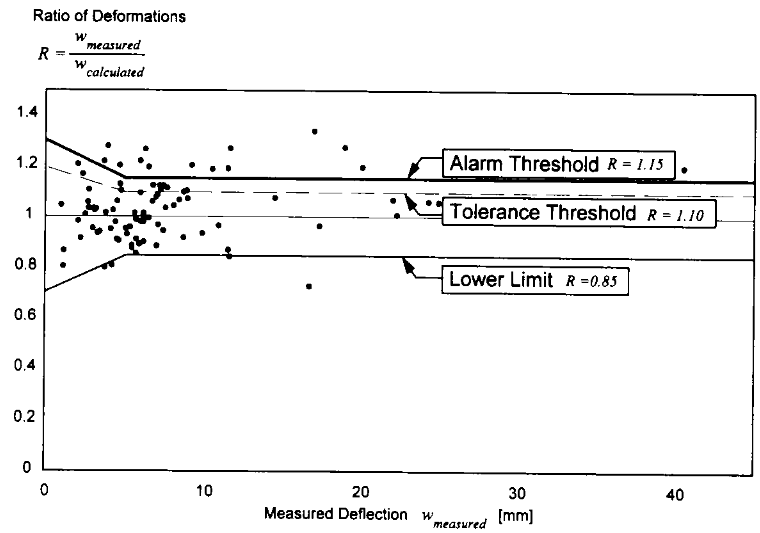

FIGURE 6 Thresholds of tolerance, alarm, and lower limit of ratio of measured to calculated deflections.

threshold for bridges presenting deflections smaller than 5 mm is less severe.

Alarm Threshold

A ratio of measured to calculated deflections exceeding 1.15 is the signal of cracking that can affect the durability of the bridge. This limit constitutes the alarm threshold for bridge authorities to keep a close eye on the bridge behavior.

Lower Limit

A measured deflection smaller than the calculated value means that the stiffness is underestimated or that fixities have been neglected in the computational model, which can heavily load some parts of the bridges. To prevent such cases, a lower limit is set at 0.85 for the ratio of measured to calculated deflections, with more tolerance for bridges that have measured deflections less than 5 mm.

Alarm Threshold of Deflections Similarity

In similar fashion, three limits for the lack of similarity ($R - R_{adj}$), where R_{adj} is the ratio of measured to calculated deflections in the span adjacent to the loaded span (average of the right and left span for intermediate spans), have been defined as thresholds for satisfactory behavior, as shown in Figure 7.

Tolerance Threshold

The tolerance threshold for the lack of similarity has been set at 0.10. For bridges exceeding this threshold, special attention should be paid to checking the presence of cracks. The tolerance threshold for bridges presenting measured deflections smaller than 10 mm is less severe.

Alarm Threshold

An ($R - R_{adj}$) exceeding 0.15 constitutes the alarm threshold for bridge authorities to increase the frequency of inspection of the bridge. The alarm threshold is less severe for bridges with measured deflections less than 10 mm.

Lower Limit

A negative ($R - R_{adj}$) should not be less than −0.10. Such a negative value for the lack of similarity typically results from an inappropriate calculation model. For bridges having measured deflections less than 10 mm, the lower limit is less severe.

Application of Criteria

The application of criteria led to the establishment of a list of bridges from the data base that need to be more frequently inspected. Eighteen of these bridges violating either of the alarm thresholds are shown in Figure 8. Observations of these bridges showed the presence of cracking. While bridges built by incremental launching showed an irregular pattern of cracking and microcracking, cast-in-place bridges showed serious cracking and one of them is currently being investigated for possible reinforcement because of cracking and excessive

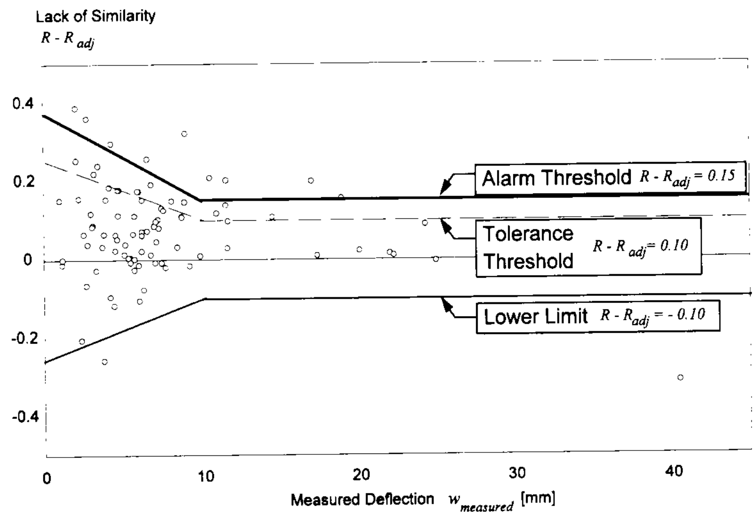

FIGURE 7 Thresholds of tolerance, alarm, and lower limit of lack of similarity.

deformation. This shows that there is a correlation between the short-term behavior and the durability of the structure. Thus, information gathered during the load test can be used for early detection of potential disorders in bridges.

Recommended Level of Post-Tensioning

A more detailed analysis of 20 bridges showed that the level of post-tensioning plays a prime role in the behavior of the bridge. The variable chosen to characterize the amount of post-tensioning used in a bridge is the level of load balancing, defined as the ratio of the balancing loads induced by the curvature of the tendons (9) to the dead weight of the superstructure. The recommended level of load balancing can be expressed as a function of the performance requirements, which depend on the importance of the bridge and its service conditions. Three broad categories are proposed below.

The high requirement level is recommended when practically no cracking is allowed under the code service loads. This requirement applies to bridges that are important, highly loaded, or in aggressive conditions. In these cases, a load balancing level of 90 percent of permanent loads is necessary to achieve a satisfactory behavior.

The normal requirement level applies to bridges for which limited cracking may be accepted, but should in no case affect the bridge durability. In this case, a load balancing level of 80 percent is recommended.

For bridges with lower loads, of less importance, and in favorable conditions, a low requirement level can be accepted. In these bridges a load balancing level of 70 percent is sufficient. Cracking under service loads will not be prevented but its evolution should remain limited.

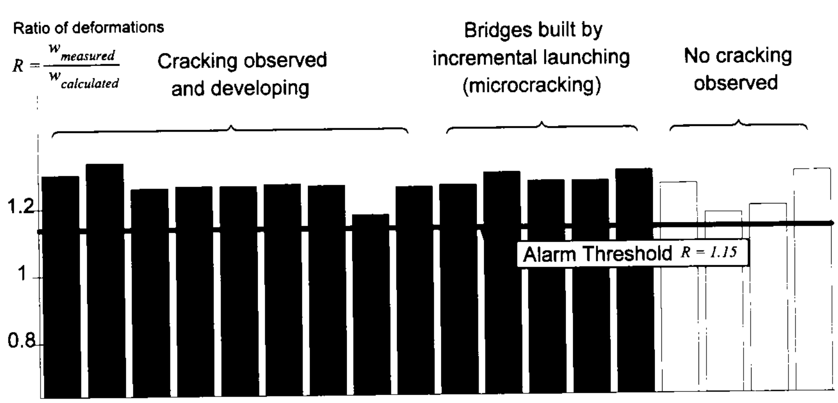

FIGURE 8 Observations on 18 bridges exceeding alarm threshold.

In special cases, a load balancing level of 60 percent or less can be sufficient. Such cases should be appreciated by the owner and the bridge designer. Typical examples are bridges with spans not exceeding 200 m, massive slab bridges, bridges with straight post-tensioning cables, and lightly loaded bridges located in mild environments.

Conclusions

Load testing of bridges is an efficient means to obtain qualitative and quantitative information on the actual behavior of the structure; this type of information has also been collected for the dynamic properties of bridges (*10*). An acceptance load test, performed on a new or recently renovated structure (*11*), is a necessary reference point for the start of the maintenance of the structure. The methodology proposed above should produce an adequate load test and a proper evaluation of its results.

The importance of elements usually not considered in the design has been shown, since reinforced-concrete parapets or an asphalt wearing surface will contribute to the stiffness of the bridge during the load test. The concrete's modulus of elasticity should be measured on molded samples, on drilled cores, or by ultrasonic measurements. This last method is very cost-effective provided a proper calibration has been made to account for local aggregates.

The thresholds presented above define the acceptable behavior of a bridge under a load test. If these thresholds are exceeded, more attention should be paid to the bridge. A correlation is evident between passing the thresholds and abnormal long-term behavior. As such, a load test not only yields information about the current condition of the structure, but also gives some insight into its future performance. This is a precious tool for maintenance operations, as the more critical structures can be identified at a very early stage.

An adequate level of post-tensioning (or prestressing) has been shown to be instrumental in ensuring proper behavior. A level of load balancing ranging from 70 to 90 percent of the dead weight should ensure proper behavior, depending on the performance requirements.

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