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STRESS REDUCTION FACTOR FOR FATIGUE ASSESSMENT OF HIGHWAY BRIDGES

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The stress reduction factor to correct for the difference in calculated and measured stresses in bridges is studied. Stress measurements are carried out with control trucks 20 tons in weight and traffic loads on seven bridges on express highways. Values of stress reduction factors are evaluated from both stresses due to control trucks and equivalent stress ranges due to traffic loads during a single day.

Keywords : fatigue, stress reduction factor, highway bridge

1. INTRODUCTION

It had been considered in the past that there was little chance of a highway bridge in Japan being subjected to a load condition corresponding to the design live load, and therefore, fatigue was not considered to be a serious problem. However, with the increase in the volume of traffic which includes many heavy weight trucks in recent years, the load conditions which exceeded the design live load is no longer a rarity. As a result, fatigue damage has begun to appear at various parts of bridges[1], and fatigue is becoming something that can no longer be ignored in highway bridges. Accordingly, it is thought that fatigue is an item that should be assessed in Japan also in the design of highway bridges and in the evaluation of damage and soundness of existing bridges.

Damage due to fatigue progresses gradually over a long period of time, and rather than the maximum stress which may occur during the life of the bridge, the governing factors are the ranges of stress fluctuations that are repeated regularly and the number of repetitions of these. Therefore, it becomes important to accurately evaluate the stress excursions which are produced actually by normal traffic loads[2)~4)], at the various parts of the bridge where fatigue would be a problem. Furthermore, since fatigue does not occur so catastrophicly compared with other bridge critical conditions such as buckling, the concept concerning safety should naturally be altered.

It has been recognized that stresses occurring in bridge members do not necessarily coincide with calculated stresses in design. The authors showed in a previous paper[2] that in evaluating fatigue damage the ratio between stress values actually produced in bridge members to live loads and calculated stress

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values (hereafter called stress reduction factor α) has a very great influence. The results of loading tests[4] in the past indicated that the value of α were less than 1.0 in many cases. Fisher used stress reduction factors, the values being 0.7 (cantilever bridge), 0.5 (simple girder bridge), and 0.75 (arch bridge) in evaluation of fatigue damage of existing bridges[5], and in calculation of design cycles of loading[6]. Therefore, if fatigue assessment were to be done without considering the stress reduction factor, the result would be prominently on the conservative side. Especially, at present, when design of highway bridges is pointed toward load and resistance factor design, this stress reduction factor cannot be ignored.

The difference between calculated stress and actually occurring stress is produced from the differences between analysis models of structures based on various hypotheses and actual behaviors of structures, and the principal causes are considered to be the impact fraction, lateral distributions loads between girders, loads carried by floor decks and secondary members. Therefore, it is thought that an extremely large number of factors such as bridge structural type, number of girders, arrangement of girders, relative positions of vehicle lanes and girders, and relative stiffnesses of girders and floor decks have influences on the stress reduction factor, and to determine the value theoretically is a very difficult matter. In the study reported here, as research of the first stage regarding such a problem, the approximate properties and trends of stress reduction factors in bridges of a number of typical types on expressways were investigated based on the results of stress measurements when loaded with control trucks and when under actual traffic loads in service. First of all, studies were made of stress reduction factors obtained from stresses under control truck loading in this study. Since stress range is the stress variable of primary interest in the evaluation of fatigue damage, stress reduction factors which are determined from the equivalent stress range under actual traffic loads are also studied.

2. METHOD OF STRESS MEASUREMENTS AND STRESS ANALYSIS

The bridges taken up in this study were the five of Takamatsu No. 1 Bridge, Katayama Viaduct (reinforced concrete bridge portion and composite girder bridge portion), and Sagamigawa Bridge on the Tomei Expressway, and Uenohara Bridge (truss bridge portion and composite girder bridge portion) and Komiya Overpass Bridge on the Chuo Expressway. The outlines of the individual bridges are given in Table 1. All of these bridges, including their approaches, and pavement surfaces in very good condition. Mounting of strain gauges in case of steel members was done on removing paintings to expose steel surface and smoothing surfaces with sandpaper. At reinforced concrete bridge portions (Katayama Viaduct), concrete was chipped away to expose main reinforcing bars, and strain gauges were attached on polishing the bars to obtain smooth surfaces. At parts of prestressed concrete bridges, concrete surfaces were smoothened and strain gauges were attached to these surfaces.

Stress reduction factors were examined on all of the bridges in Table 1 using the stresses on passage of control vehicles. The control vehicles were three-axled trucks of total individual weights approximately 20 tons close to T-20 truck in design[7], with weights of front and rear wheels measured by axle-load scales before traveling. Stresses were measured in a condition where there were no vehicles in front or back of the control truck with the truck passed three or four times down the middle of each lane at normal speed.

In stress analyses, analysis models the same as in design calculations were set up, influence lines of vehicles on lines of travel were determined, and the control trucks used on the respective bridges were loaded on. The methods of stress analyses on the various bridges are given in Table 1. The stress reduction factors were determined from the measured stress values and the calculated stress values obtained in this way.

For the calculated stress values in determining stress reduction factors, both the cases including and not including the impact fraction specified in the Highway Bridge Specifications[7] were used.

At Takamatsu No. 1 Bridge and Katayama Viaduct on the Tomei Expressway, stress variations were measured for 20 consecutive minutes every hour for 24 hours of a day. Cycle counting of the stress ranges

Table 1 Outlines of Bridges Examined.

ROUTE	BRIDGE	BRIDGE TYPE	LENGTH	WIDTH	CALCULATION METHOD
Tomei	TakamatsuNo.1	P.C. post-Ten. T section Simple	27.76m	13.154m	simple supported girder
	Katayama Viaduct	Steel composite girder	47.30m	12.60m	grid structure effective width
	Katayama Viaduct	3 span continuous girder,R.C.Hollow	35.571m	12.60m	grid structure
	Sagamigawa	2 span continuous girder,P.C.Box	73.90m	16.35m	grid structure
Chuo	Uenohara	Truss	84.115m	12.101m	truss
	Uenohara	Steel composite girder	28.039m	12.101m	grid structure effective width
	Komiya	Steel Box	50.149m	12.50m	grid structure

were performed on the results employing the Rain-flow Method to obtain the equivalent stress ranges. Takamatsu No. 1 Bridge and Katayama Viaduct are respectively located approximately 1 800 m and approximately 700 m west of the axle-load weighing meters installed on the through-traffic lanes to Tokyo near the Nihondaira Parking Area. Therefore, it is possible to measure the weight of an vehicle with the axle-load weighing meters immediately after crossing these bridges. Here, the array of axle-loads in the cruising and passing lanes which were obtained using the axle-load weighing meters at the same time as when stress measurements were made, were applied to the analysis models of the individual bridges. Stress variations were calculated by moving these at intervals of 1/100 sec.. Cycle counting of the stress range were performed by the Rain-flow Method and the equivalent stress ranges Seq were calculated by Eq. (1). Further, the stress reduction factor was determined from the equivalent stress range. At that time, the locations of vehicles in road lanes were taken to be constant with width of 1.75 m regardless of vehicle model, with distances between vehicles those when the axle-load weighing meters was passed.

$$S_{eq}=\sqrt[3]{\frac{\sum S_i^3}{N}} \quad \cdots\cdots (1)$$

where, S_i is stress range and N is the total number of stress ranges. This equivalent stress range corresponds to application of the Linear Damage Law (Modified Miner's Law) with the gradient of the S—N line as —1/3.

3. STRESS AT PASSAGE OF CONTROL TRUCK AND STRESS REDUCTION FACTOR

The measured values of stress (average values) at the times of passage of the control trucks at the various bridges, the calculated values of stress, and the stress reduction factors calculated from them are shown in Fig. 1. Impact fractions are considered in the calculated stresses. The characteristic results for the individual bridges are as follows :

(1) Katayama Viaduct, and Uenohara Bridge (Composite Girder)

In the cases both of the control truck traveling over the cruising lane and the passing lane, stress reduction factors were low near the applied loads, becoming higher with increased distance. This indicates that the load lateral distribution in an actual bridge is over a wider area than hypothesized in stress calculations. The stress reduction factors obtained for the maximum calculated stresses were 0.61 for Katayama Viaduct and 0.78 for Uenohara Bridge. These values are slightly on the high side compared with data compiled by Ministry of Construction in 1966[4], but may be reasonable when considering that analyses are performed as grid structures.

(2) Komiya Overpass (Steel Box Girder Bridge)

The stress at the bottom flange directly below the wheel load when the control truck traveled in the cruising lane was maximum. In other cases, however, the measured values at the two ends of a box girder flange were roughly equal, indicating that it is appropriate for modeling of analysis to be done with the box girder replaced by a bar element for a grid structure. The stress reduction factor obtained with the maximum calculated stress was 0.8.

(3) Uenohara Bridge (Simple-Span Steel Truss)

The crusising lane was located slightly toward the shoulder near the middle of the highway width. When the control truck was driven, the measured value in the main truss on the shoulder side was slightly larger compared with that of the main truss on the passing lane side. However, the stress reducticn factor was higher for the passing lane side, and the load was extremely eccentric in case of traveling the passing lane. In this case, the stress reduction factor was exceedingly low on the passing lane side main truss in comparison with the main truss on the shoulder side, and the influence of load distribution was distinctly seen.

(4) Takamatsu No. 1 Bridge (Prestressed, Post-tensioned Simple-Span T-Girder)

The stress reduction factor was high near the loading point and became lower with increased distance from the loading point. This indicates that the actual load lateral distribution was over a smaller area than in calculations. The stress reduction factors obtained for the case of calculated stress maximum and the case of measured stress maximum were 0.55 and 0.73, respectively.

(5) Sagamigawa Bridge (Prestressed Concrete Two-Span Continuous Box Girder)

Stress reduction factors were high in box girders close to the load, while among box girders, the factor was higher the closer to the load. Compared with the behavior of Komiya Overpass, it may be said that load distribution behaviors differ greatly between steel and concrete bridges even though both are box cross section bridges. The stress reduction factor at the location where calculated stress was the maximum was 0.74.

(6) Katayama Viaduct (Reinforced Concrete Hollow Slab)

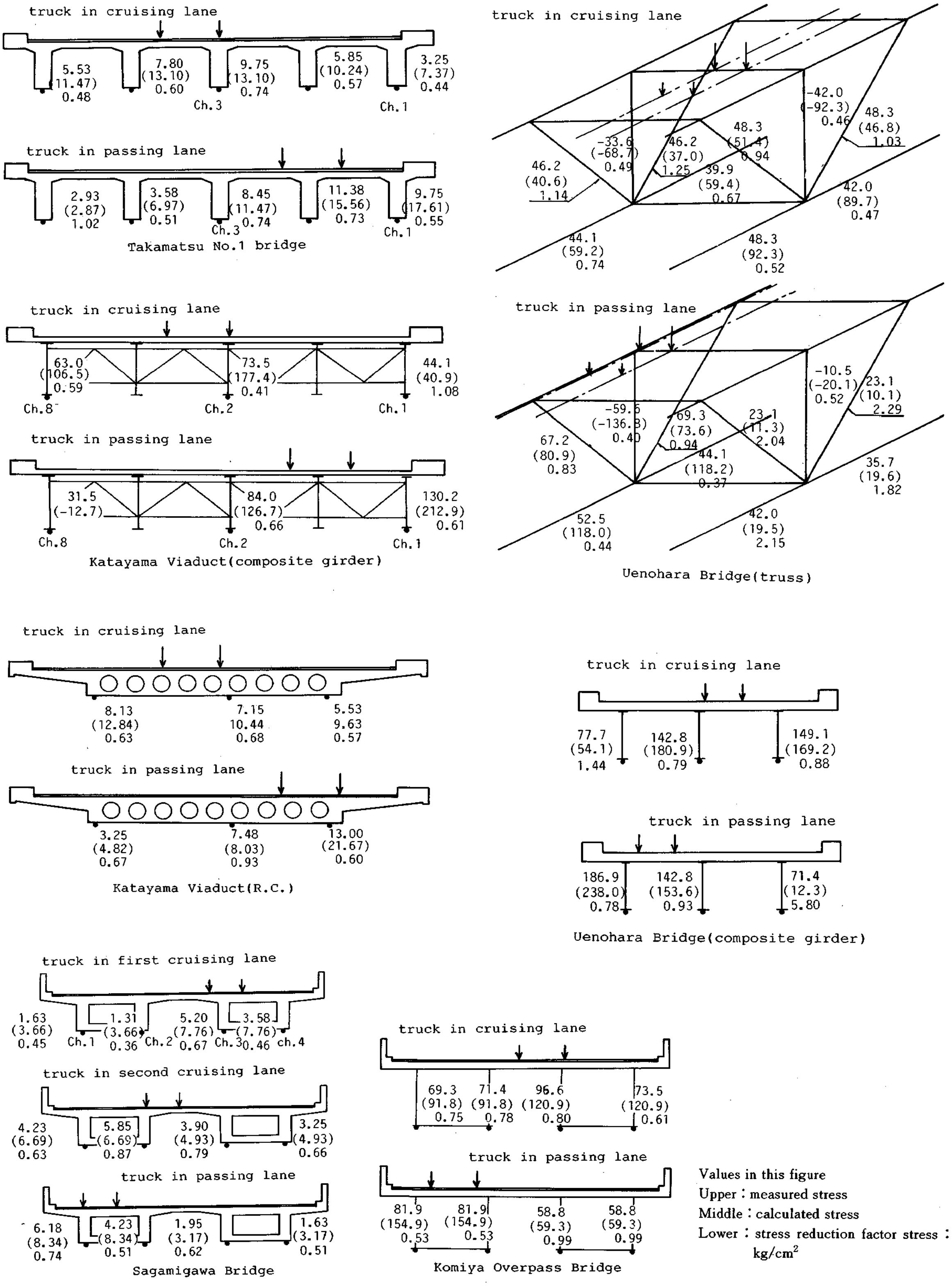
The measured values when the control truck traveled the cruising lane and when it traveled the passing lane were in the same order indicating the appropriateness of the structural analysis model having been made a grid structure. The stress reduction factor at the location where the calculated stress is maximum was 0.6.

The stress reduction factors when including and not including impact fraction in calculated values of stress are shown in relation to calculated values in Fig. 2. The values of impact fraction by the Highway Specifications and mean values of stress reduction factors of the individual bridges are shown in Table 2. In the steel girder of (a), the stress reduction factors are all under 1.0 with the exception of three points with low calculated values of stress (girder distant from the loaded lane) and a trend of decrease as stress becomes higher is seen. When stress reduction factors are compared for Uenohara Bridge (three main girders) and Katayama Bridge (five main girders) which are both simple-span composite-girder steel bridges, Uenohara Bridge has higher factors as a whole, and it can be conjectured that stress reduction factor is influenced to a considerable degree by the number of main girders and by the resulting load lateral distribution.

The stress reduction factors for the various members of the simple-span steel truss bridge (Uenohara Bridge) in Fig. 2(b) show the highest values for diagonals and about the same for bottom chord members and vertical members.

With the concrete bridges shown in Fig. 2(c), there is hardly any difference depending on structural type recognizable for stress reduction factors with the values scattered between 0.5 and 0.75 for parts of high stresses.

As described above, the stresses actually occurring due to live loads differ considerably from design calculation stresses, and under conditions of high stress affecting fatigue damage of members, the stress reduction factors based on calculated values including impact fraction are all under 1.0, while the values of stress reduction factors based on calculated values not including impact fraction are also under 1.0 in most cases. Furthermore, although from only a small number of measurements, the load lateral distribution actions between girders thought to be the principal causes of such behaviors are approximately seen to be larger in actual bridges than estimated in design calculations in case of steel girders and smaller in actual



Values in this figure
Upper : measured stress
Middle : calculated stress
Lower : stress reduction factor stress : kg/cm^2

Fig. 1 Measured Stress, Calculated Stress and Stress Reduction Factor.

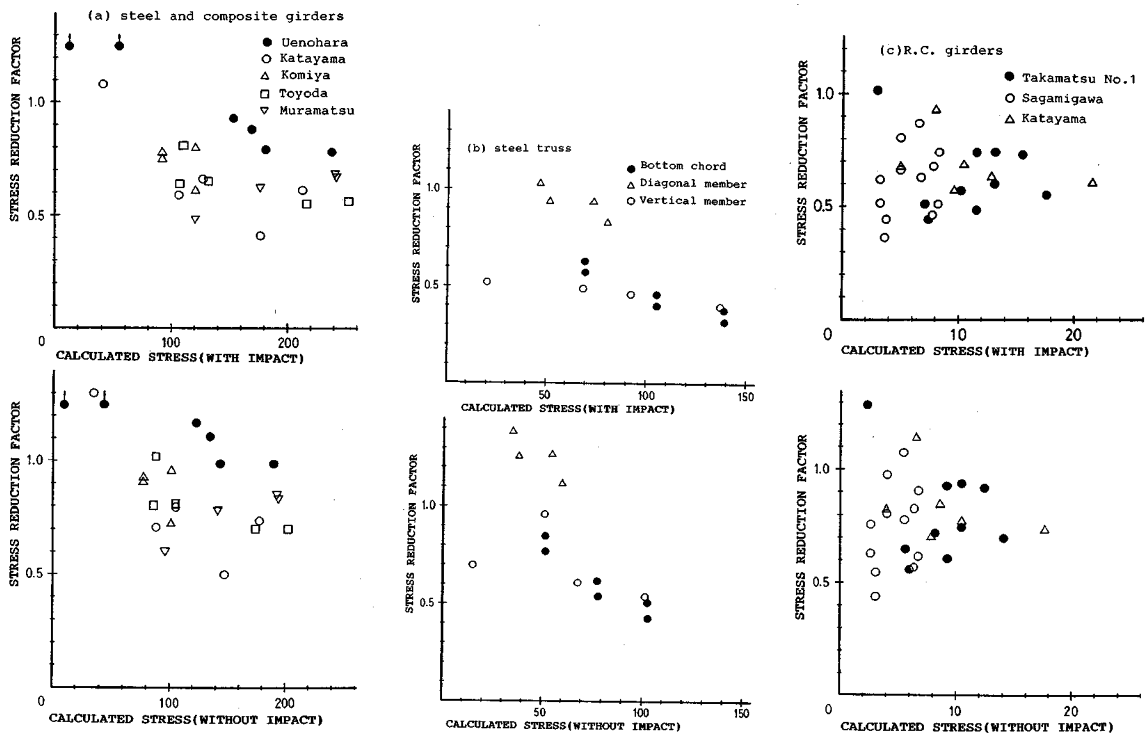


Fig. 2 Stress Reduction Factors in Various Types of Bridges.

Table 2 Mean values of Stress Reduction Factor.

BRIDGE	IMPACT FRACTION	STRESS REDUCTION FACTOR	
		WITH IMPACT	WITHOUT IMPACT
Takamatsu No.1	0.260	0.64	0.81
katayama(steel)	0.207	0.67	0.81
Katayama(R.C.)	0.235	0.68	0.84
Sagamigawa(R.C.)	0.231	0.60	0.75
Uenohara(steel)	0.259	0.85	1.07
Komiya	0.200	0.75	0.90
Toyoda(steel)*	0.253	0.64	0.81
Muramatsu(steel)**	0.250	0.65	0.82

*Tomei expressway, 3 span continuous girders with three girders 28.62 + 29.00 + 28.63m

**Tomei expressway 3 span continuous girders with four girders 3 x 30m

bridges in case of concrete girders.

4. STRESS REDUCTION FACTORS UNDER SERVICE LOADS

The volumes of traffic and the ratios of trucks when stress measurements were made at Katayama Viaduct (composite girder) for 20 minutes of every hour for 24 hours are shown in Fig. 3. The distributions of vehicle weights measured at the same times on the same day using axle-load weighing meters in the through-traffic lanes are shown in Fig. 4. For Takamatsu Viaduct, stress measurements were made on a different day, and traffic volumes and vehicle weights were measured similarly, the results geing almost the same as those given in Fig. 3 and 4.

The equivalent stress ranges for the Measuring Locations (Ch.) 1, 2 and 8 (see Fig. 1) at bottom flanges of Katayama Viaduct (composite girder) are shown in Fig. 5. The values for equivalent stress

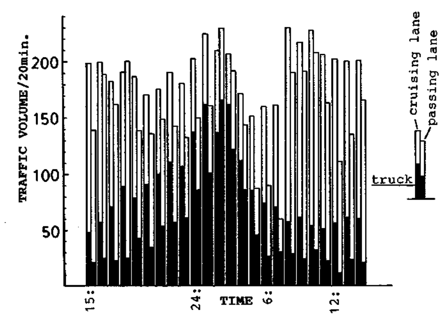


Fig. 3 Traffic Volumes for 20 Minutes.

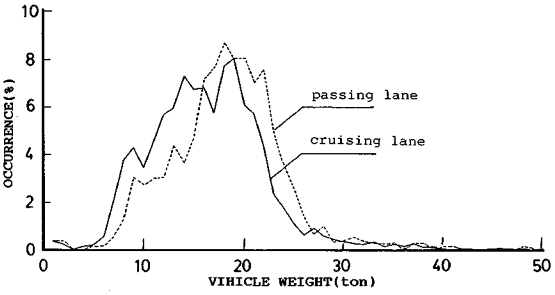


Fig. 4 Distribution of Vehicle Weight.

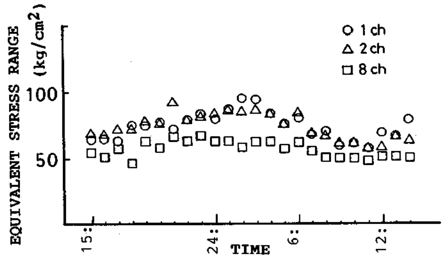


Fig. 5 Equivalent Stress Ranges (Katayama).

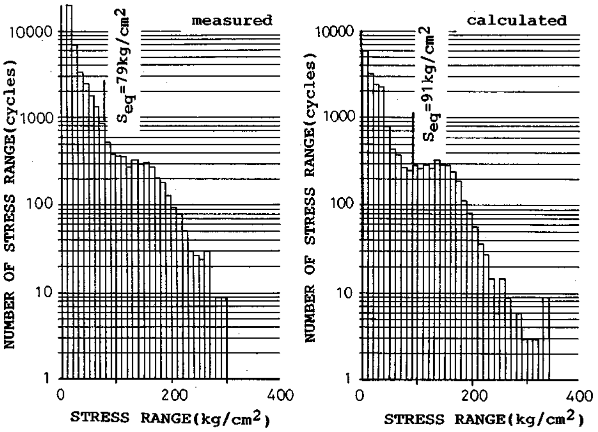


Fig. 6 Measured and Calculated Stress Ranges (Katayama).

ranges are about the same for the end girder on the passing lane side (Ch. 1) and the middle girder (Ch. 2), with a slightly lower value for the end girder at the shoulder (Ch. 8). During the nighttime to early morning, the greater part of traffic consists of heavy trucks, while moreover, the volume of traffic is large, and during this time a slight trend for equivalent stress range to be on the higher side is seen. However, the design live load stress for Measuring Locations 1, 2, and 8 is 850 kg/cm^2, the equivalent stress ranges being from 0.06 to 0.12 times the above value.

Stress variations due to service loads can be obtained by directly applying axle-weight measured by axle-load weighing meters at the through-traffic lanes to the individual bridges. The location of loading lane at this time was assumed to be the same as for the control truck and the same influence line was used. Therefore, errors due to differences in vehicle lineups, changes in distances between vehicles, delays in loading locations, variations of vehicle widths, etc. occurring between bridge and axle-load weighing meter (700 m for Katayama Viaduct, 1 800 m for Takamatsu No. 1 Bridge) are included in the results obtained by these analyses. However, the equivalent stress ranges are average-type quantities, and it is possible for overall trends to be examined. Impact fractions are not included in the calculated stresses in this case.

The spectrum of stress ranges obtained applying the Rain-flow Method to measured and calculated stress values of all data for a 24-hour period at Measureing Location 1 on Katayama Viaduct are shown in Fig. 6. The distributions of measured values are shifted towards the smaller side than calculated values at all of the measuring locations.

The stress reduction factors calculated for equivalent stress ranges every hour are shown in Fig. 7. The stress reduction factors at the various hours are fairly scattered, but all are slightly higher than the factors (not including impact) obtained for control truck loads. At Katayama Viaduct (composite girder),

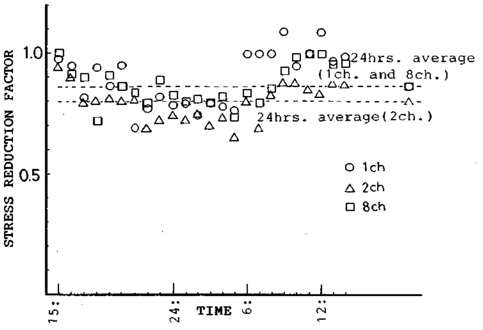


Fig. 7 Stress Reduction Factors (Katayama).

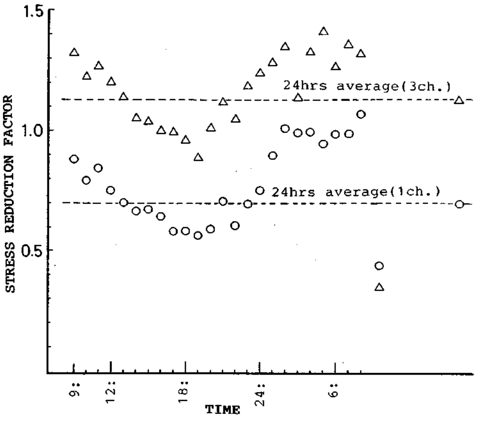


Fig. 8 Stress Reduction Factors (Takamatsu).

a trend was seen for stress reduction factor to become lower during the nighttime to early morning when volume of traffic was large with most of the traffic consisting of heavy trucks to pose severe load conditions. In contrast, at Takamatsu No. 1 Bridge (prestressed concrete), the stress reduction factor in the hourband of severe load was higher than average, being more than 1.0 in places. Such a trend is thought to have been related to the difference seen between steel and concrete girders regarding load lateral distributions and stress reduction factors in Fig. 1.

Similarly, the stress reduction factors for equivalent stress ranges of Measuring Locations 1 and 3 on Takamatsu No. 1 Bridge are shown in Fig. 8. At Measuring Location 3 where the load of the cruising lane was applied directly above, the stress reduction factor on average for 24 hours exceeded 1.0. The stress reduction factor for equevalent stress range at Measuring Location 1 where load was not directly applied was close to the stress reduction factor when control truck load was applied. Such a trend is considered to have been due to the load lateral distribution actually occurring in a concrete girder being smaller than estimated by calculations as described in 3.

The maximum stresses, equivalent stress ranges, and the stress reduction factors determined from them obtained by calculations and measurements during the 24-hour measurement period for the girders of Katayama Viaduct and Takamatsu No. 1 Bridge are shown in Table 3. The stress reduction factors obtained for equivalent stress ranges under service loads indicated a trend of being slightly larger compared with the stress reduction factor obtained for the stress when applying the load of the control truck, but these may be considered to have been roughly the same when the accuracies of the analyses and measurements are taken into account. That the stress reduction factor for the equivalent stress range was slightly higher may be said to have been a result which could be expected to some degree because equivalent stress was calculated using all stress range components, low stress range components was dominant in the

Table 3 Maximum Stresses, Equivalent Stresses and Stress Reduction Factors.

		Maximum Stress			Equivalent Stress		
		Calculated	Measured	Factor	Calculated	Measured	Factor
Katayama	Ch.1	357	315	0.88	91.0	79.1	0.87
	Ch.2	336	304	0.91	97.5	77.7	0.80
	Ch.8	262	252	0.96	67.2	59.2	0.88
Takamatsu	Ch.1	30.9	17.9	0.58	8.0	5.7	0.71
	Ch.2	30.9	17.9	0.58	7.9	6.2	0.78
	Ch.3	27.6	27.6	1.0	7.6	8.7	1.14
	Ch.6	22.8	19.5	0.86	7.3	7.6	1.04
	Ch.9	21.1	19.5	0.92	6.6	5.9	0.89

Stress: kg/cm^2

spectrum of stress range, and because in Fig. 2 stress reduction factor was seen to have a trend of being high at low stress. Further, the influence lines used in calculations differed considerably from actual behavior, and because of this it is thought the difference appeared prominently in case of successive travel of vehicles in a lane or when vehicles traveled in parallel in adjacent lanes.

5. CONCLUSION

Stress reduction factors in expressway bridges were studied based on the results of stress measurements at actual bridges in service. The principal results obtained in the study are as follows :

(1) Stress reduction factors when loading a control truck of specifications close to T 20 were less than 1.0 for all locations. The values for steel girders were approximately 0.6 to 0.8 showing trends of change depending on structural type and number of main girders. In concrete bridges, the values were 0, 5 to 0.75.

(2) The stress reduction factor for equivalent stress range under service load is slightly higher than stress reduction factor based on the stress at application of control truck load not including impact fraction. However, the difference is extremely small, and therefore it becomes possible for the stress reduction factor obtained by loading of the control truck to be used for assessment of fatigue.

It is considered absolutely necessary for this stress reduction factor to be considered in evaluation of fatigue design and fatigue damage, and for this purpose measurement data of even more bridges should be gathered to increase general applicability and reliability, while there are many problems needing to be solved such as the reason for the differences in values when control trucks were loaded on and the values in the equivalent stress range.

(3) Although from a very small amount of data, the stress reduction factors in case of assessment of fatigue when stresses including impact loads are the bases are thought to be about 0.65 for both steel and concrete girders. To use calculated stresses not including impact fraction in unaltered form will be to make predictions on the conservative side.

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