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Aerodynamic Effects on Suspension Bridges with Inclined Hangers

Effets aérodynamiques des ponts suspendus à câbles inclinés

Aerodynamische Einflüsse auf Hängebrücken mit schrägen Hängern

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SUMMARY

It has been reported that the inclined hangers of a suspension bridge were so weak after 16 years of service that most would probably have to be replaced. In this paper, it is analytically presented that the fatigue damage of inclined hangers is caused by their essential higher tensile force variations, in contrast with those in traditional vertical hangers. The longitudinal loadings by wind action and traction or braking of heavy vehicles, and the vertical load of inertia forces due to buffeting in gusty winds are assumed, and the latter two factors are concluded to be significant to contribute to the fatigue damage.

RESUME

On a constaté des dommages si importants dans les câbles obliques d'un pont suspendu, qu'après seulement 16 ans de service, on devra probablement en remplacer la plus grande partie. Cet article démontre analytiquement que les dommages de fatigue de câbles obliques sont plus importants que pour les suspentes verticales. Ce fait est dû aux très grandes variations de tension dues au vent et surtout au freinage des véhicules lourds et aux chocs causés par les rafales de vent.

ZUSAMMENFASSUNG

Bei einer Hängebrücke mit schrägen Hängern sollen nach 16 Betriebsjahren die Hänger so schwach sein, dass vermutlich die meisten ersetzt werden müssen. Der Beitrag zeigt auf analytische Weise, dass die Ermüdungserscheinungen an schrägen Hängern auf die – im Vergleich zu traditionellen lotrechten Hängern – wesentlich höheren Spannungsänderungen zurückzuführen sind. Untersucht wird sowohl die Wirkung von in Brückenlängsrichtung wirkenden Lasten infolge Wind und Bremsen von schweren Fahrzeugen als auch von lotrechten Trägheitskräften infolge windinduzierter Schwingungen. Die beiden letzten Faktoren werden als bedeutsam für die festgestellten Ermüdungserscheinungen erkannt.

1. INTRODUCTION

It has been reported [1,2] that the inclined hangers of a suspension bridge were so weak after 16 years of service that most would probably have to be replaced. It is thought that the revolutionary use of inclined hangers may explain their fast deterioration by fatigue, caused by greater restrictions to longitudinal movement in the deck. The use of inclined hangers was originally expected to damp the predicted oscillations of the flexible, streamlined box girder.

In this paper, it is analytically presented that the fatigue damage of inclined hangers is caused by their higher tensile stress variations, in contrast with those in traditional vertical hangers. These tensile stress variations may be attributable not only to the far higher live loads of road traffic, as frequently pointed out, but also to the greater wind-induced buffeting oscillations inevitable to a flexible, winged box girder. In the analyses, assuming the following conditions ; (1) the longitudinal load resulting from traction or braking of heavy vehicles, (2) that by wind action shifted from normal to the bridge axis, and (3) the vertical load corresponding to inertia forces determined according to buffeting in the flexural first mode shape, the estimations of fatigue damage were made.

2. ANALYTICAL PROCEDURE AND ASSUMPTIONS

The displacement and force for the given loadings were calculated by the geometrically nonlinear analysis method, usually applied to the large displacement behaviour of frame work structures, considering the axial force variations in the cables and hangers. The nonlinear variations were confirmed by incrementing the loads step by step up to the assumed maxima. The analyses were made for a model bridge having traditional vertical hangers, with two ropes located at each panel point, as well as for a bridge having inclined hangers, setting the nodal points at all the hanger connections.

The primary dimensions for the analyses were quoted from those of the Severn Bridge [3,4,5] and others were assumed appropriately ; center span length l = 987.6 m, side span length l_1 = 304.8 m, sag-span ratio of cable : 1/12, longitudinal slope : 0.5 % parabolic at center span, one cable (dia. : 50.8 cm, area : 0.116 m^2, $E_c = 2.0\times10^7$ t/m^2, weight : 2300 t), one hanger (dia. : 52.8 mm, area : 13.3 cm^2, $E_h = 1.4\times10^7$ t/m^2, length : 2.3 m at center and 1.5 m at end to abutment), suspended deck (area : 1.043 m^2, I = 1.21 m^4, $E_s = 2.1\times10^7$ t/m^2, steel weight : 11200 t, asphalt thickness : 3.8 cm), tower (flexurality to bridge axis was replaced by an equivalent tensile spring at tower top, having area : 1 m^2, E_t = 165 t/m^2, and length : 1 m). The initial hanger tensions were determined according to the dead load of the girder. The bridge elevations and the hanger connections are as shown in Fig. 1.

3. LONGITUDINAL LOADINGS

3.1 Uniform Wind Loading

Assuming the wind action shifted from normal to the bridge axis, the streamlined box girder of the Severn Bridge would be loaded with the maximum longitudinal drag force (coefficient = about 45 % at most of C_D = 0.6 for normal to the bridge axis) in 50 to 60 degrees orientation from normal [6]. The load intensity is p = 17.7 kN (1.8 tf) /Br. per one panel length (18.3 m), taking account of the design wind speed V_D = 100 mph (44.7 m/s). Fig. 1 shows the hanger tension distribution diagrams for the inclined and the vertical hangers respectively, under the uniform, longitudinal loading on all the spans of the girder. The tension variations in the vertical hangers are very low except those of the extreme end hangers with the shortest length (V1 and V86 in Fig. 1), while those in the inclined hangers are really noticeable within the hanger range different from usual array of isos-

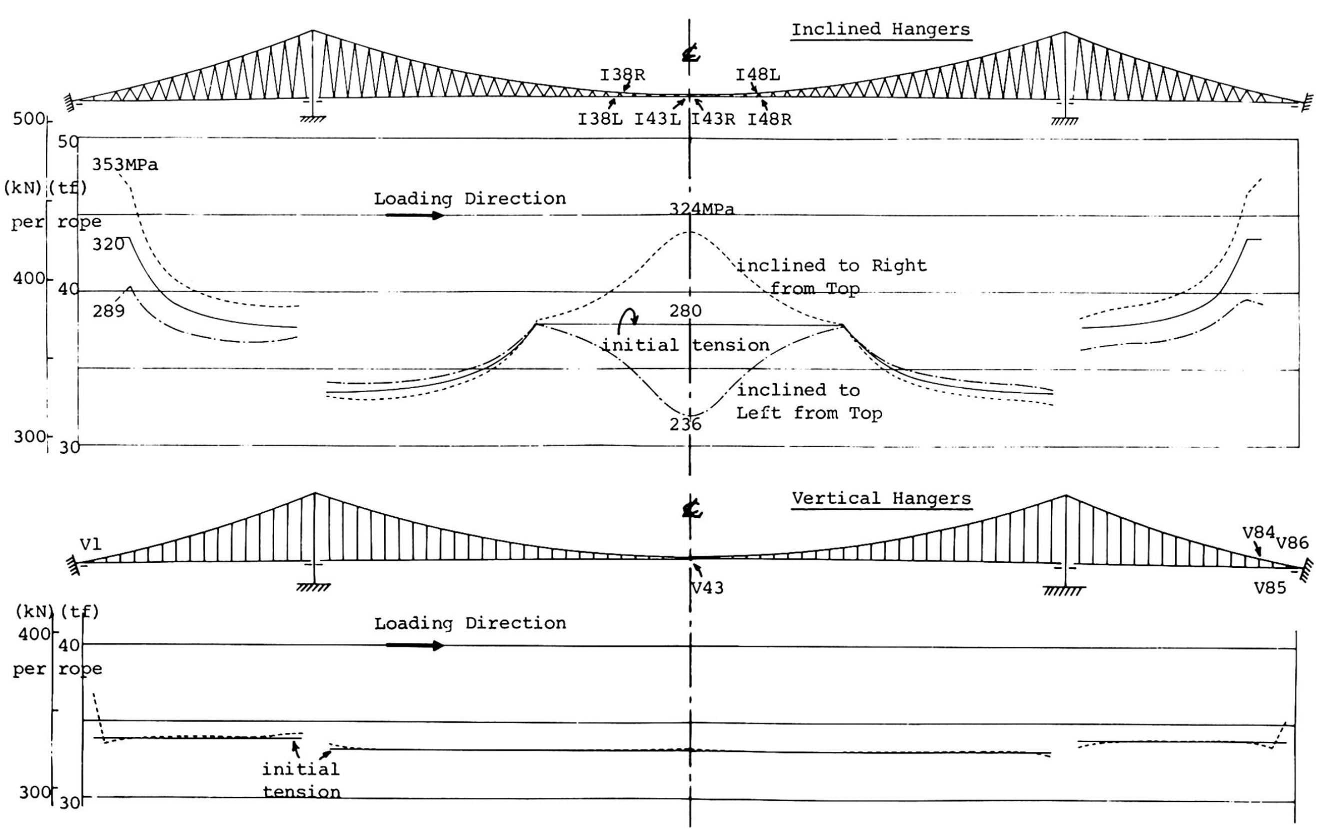


Fig. 1 Hanger Tension Distribution by Uniform Longitudinal Loading for Girder with 17.7 kN(1.8 tf) per one panel length/ Br.

celes triangle in the middle of center span and at the both ends to the abutment of side spans. In this case of loading from left to right, as shown in Fig. 1, the tension variations are different between the hangers inclined to the right from the top and those inclined to the left.

This effect of longitudinal wind loading produces only the tensile stress variation of 44 MPa (4.5 kgf/mm^2) at most at the span center point, which is not so enough to cumulate the fatigue damage, judging from the fatigue strength N.S. curve with 5 % break level in Fig. 4(e), obtained from the tests for hanger ropes [7]. The occurrence of such a strong wind as the design wind speed is quite unusual, and it may be of a return period more than 100 years. This case is concluded not to contribute to the fatigue.

3.2 Uniform Vehicles Traction or Braking Loading

As seen in the preceding analysis, the higher stress variations are essential to the inclined hangers under the longitudinal loading, compared with the vertical hangers. Taking account of the severe longitudinal load resulting from traction or braking of heavy vehicles, the occurrence of much higher stress variations would be expected. Assuming the 25 % intensity (6 kN/m) of the design live load (24 kN/m) for the Severn Bridge as a longitudinal load, p = 110 kN (11.2 tf)/Br. is to be loaded per one panel length. Incidentally, it is referred to the B.S. 5400 Specification for loads of 6.6 [8] that the nominal longitudinal load for type HA shall be 8 kN/m of loaded length. This loading condition means an arrangement of two heavy vehicles with 2 @ 220 kN (22 tf) loaded at each panel point /Br.

The hanger tension distributions are basically similar to those shown in Fig. 1 under such a severe loading on all the spans as well. Aiming at tension variations from the initial one for some specified hangers, Fig. 2 can be obtained, where it is seen that the nonlinearity for the load increment is more remarkable in the vertical hangers, particularly in the extreme end hangers with the shortest length (V1 and V86), and that the almost linear increase of variations in the inclined hangers, for instance, in both hangers at the span cenetr point (I4 3R and L) is so noticeable to produce the higher stress variation of 44 x (11.2/ 1.8) = 274 MPa (28 kgf/mm^2). As far as the longitudinal displacements of the girder are concerned, in the inclined hangers, the relatively smaller displacements of 13.4 cm in the center span and 5.4 cm in the side spans are calculated, resulting from the greater restriction effects of the inclined hangers to longitudinal movement. On the contrary, in the vertical hangers, the greater displacements are observed with 96.3 cm in the center span, varied almost linearly, and 120 cm in the side spans, varied nonlinearly, although the stress variations in almost all the hangers are very low except the extreme end ones.

Estimate the possibility of fatigue damage for this case of inclined hangers. The repeat numbers of about 1.5 x 10^5, for the stress range of 274 MPa (28 kgf /mm^2) at the span center point, can be taken from the fatigue strength curve with 5 % break level in Fig. 4(e). How often would the occurrence of such a higher stress variation be expected. Judging from the current news that in 1981 the Severn Bridge carried 12 million vehicles [1], the average vehicle numbers loaded at each panel length /Br. is approximately, assuming the heavy vehicle mixed ratio to be 0.25,

$$12 \times 10^6 \times \underset{\text{two ways}}{\frac{1}{2}} \times \underset{\text{hours/year}}{\frac{1}{365 \times 24}} \times \underset{\text{panels}}{\frac{1}{86}} \times 0.25 \doteqdot 2 \text{ /hour,}$$

which coincides with that of the assumed condition. Furthermore, taking account into 16 years of service mentioned in the beginning, the time length amounts to 16 x 365 x 24 $\doteqdot$ 1.4 x 10^5 hours, and corresponds to 2.8 x 10^5 repeat cycles in two ways of the bridge. This analysis would imply a sufficient estimation to induce the fatigue damage for the inclined hangers with higher stress variation. This is the case for the extreme end hangers among the vertical ones as well.

4. VERTICAL LOADING DUE TO BUFFETING

It is a matter of concern to know how high the tension variations for the inclined hangers are under a vertical load. Taking account of the wind-induced buffeting oscillations, which were inevitable to a flexible, winged box girder in gusty winds, the inertia force determined according to a flexural oscillation in the symmetric first mode shape would be a suitable vertical loading to evaluate the fatigue damage. As far as the buffeting oscillations in a winged, plate-like section are concerned, some experimental or theoretical data are available [9,10,11]. Referring to the experimental data (f_T/f_z = 2.8) of vertical RMS responses in a turbulent flow with intensity of 7 % [9], and assuming a possible amplitude of A = 90 cm at the span center point, which probably corresponds to the amplitude at wind speed of about 40 m/s, a set of inertia forces ($mA\omega_z^2\Phi(x)$) of (1) and (2) is determined in the form of 6.32 kN/m (0.645 tf/m) x $\Phi(x)$ /Br. for the girder and 2.62 kN/m (0.267 tf/m) x $\Phi(x)$ /Br. for the cables, as shown in Fig. 3(*a*), where m is the mass, ω_z ($=2\pi f_z$) the circular natural frequency and $\Phi(x)$ the mode shape.

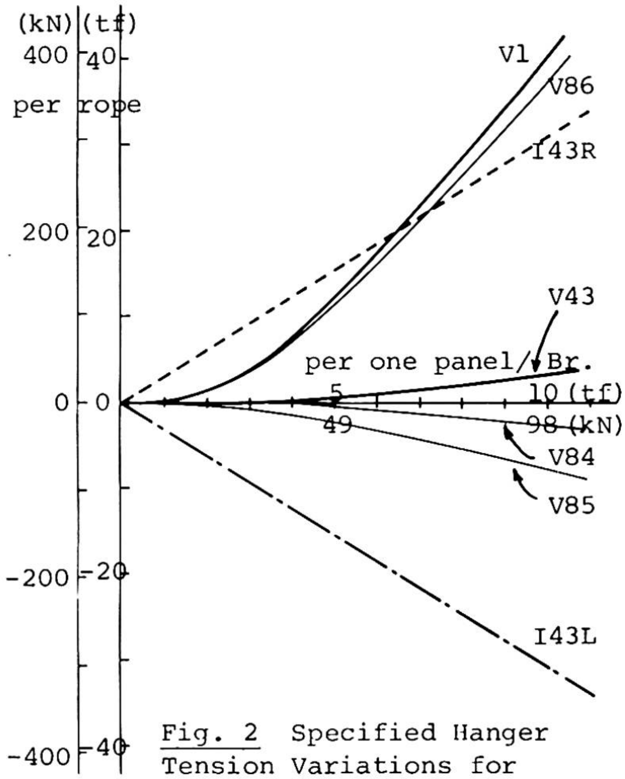


Fig. 2 Specified Hanger Tension Variations for Uniform Longitudinal Loading for Girder

Figs. 3(b) and (c) are the hanger tension distribution diagrams under the vertical loadings of type (1) and (2) for the inclined and the vertical hangers respectively. The nonlinearity in this analysis up to the assumed load intensity is very small for both cases of hangers. On estimating the fatigue damage under buffeting oscillations, the stress variations are to be evaluated in the difference of those for the loadings (1) and (2). The maximum stress range in the inclined hangers in Fig. 3(b) gets to 282 MPa (28 kgf/mm^2) in the vicinity of the hanger I38R, inclined to the right from the top, and also the hanger I48L, inclined to the left. On the contrary, the stress range of vertical hangers is, as shown in Fig. 3(c), 42 MPa (4.3 kgf/mm^2) at most at the span center point, although only the extreme end hangers get 152 MPa (16 kgf/mm^2).

Evaluate the extent of contribution to the fatigue deterioration due to buffeting oscillations, aiming at the inclined hanger with maximum stress variation. For this purpose, the cumulative fatigue damage ratio would be a significant index. Considering the relevant factors ; (*a*) the frequency of occurrence f(V) of wind speed V, (b) the vertical RMS response σ_z of buffeting to wind speed, (c) the peak (amplitude) y distribution of random oscillation z, (d) the relation between stress variation σ_t and peak response y, and (e) the fatigue strength curve (relation between stress range σ_t and repeat numbers N), the cumulative ratio can be calculated by

$$\gamma = \int_V \int_y \{ f(V)p(y,V)/N(y) \} \, dVdy.$$

The respective relations are in detail described in Fig. 4. Using the frequency of occurrence of wind speed given in B.S. 5400 draft [12] and the Rayleigh distribution assumed as the peak distribution p(y,V), the ratio is γ = 0.032 per year, so that over 0.5 for 16 years of bridge service. This may be enough to represent that the wind-induced buffeting oscillations make a significant contribution to the fatigue deterioration.

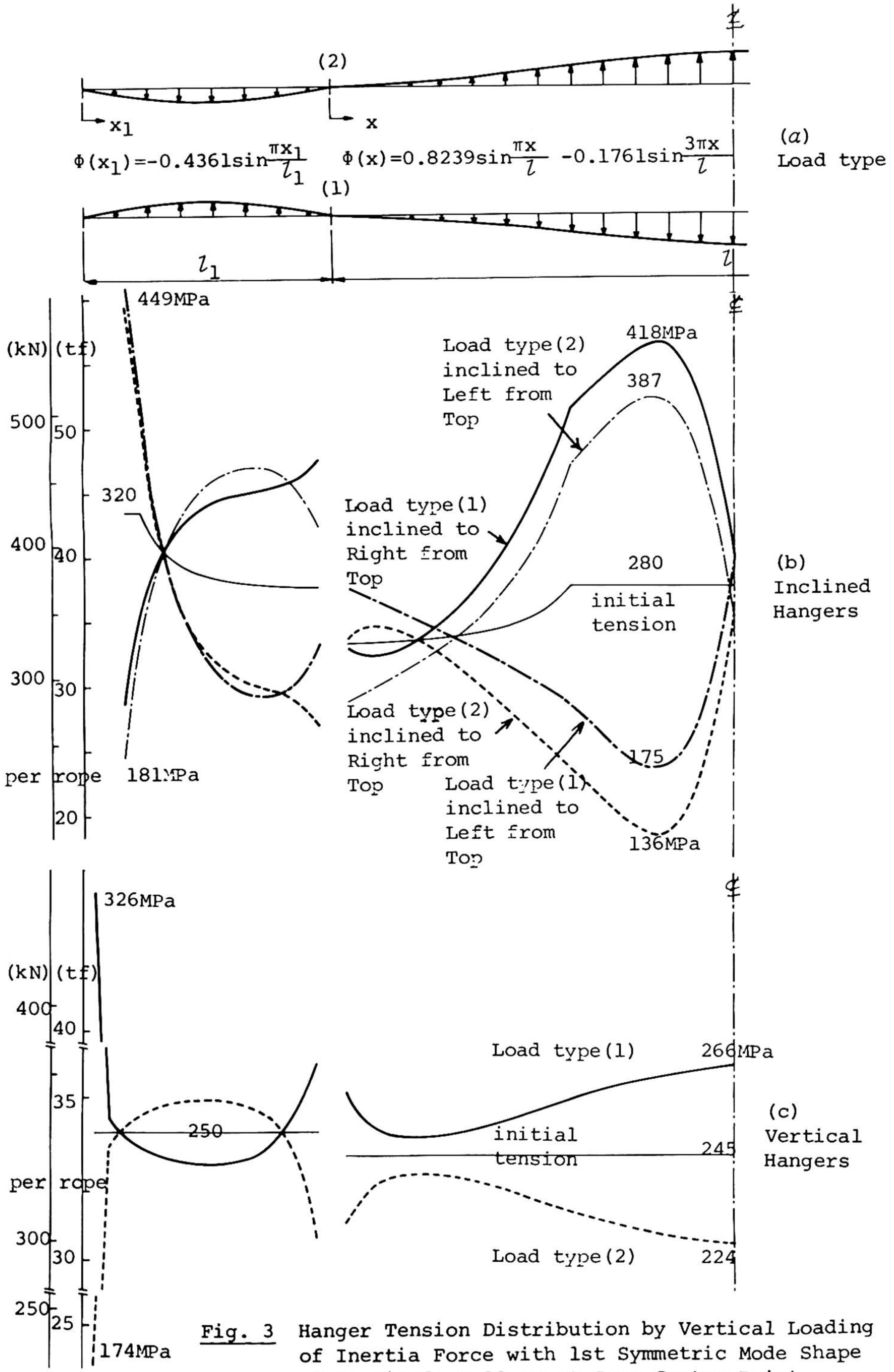
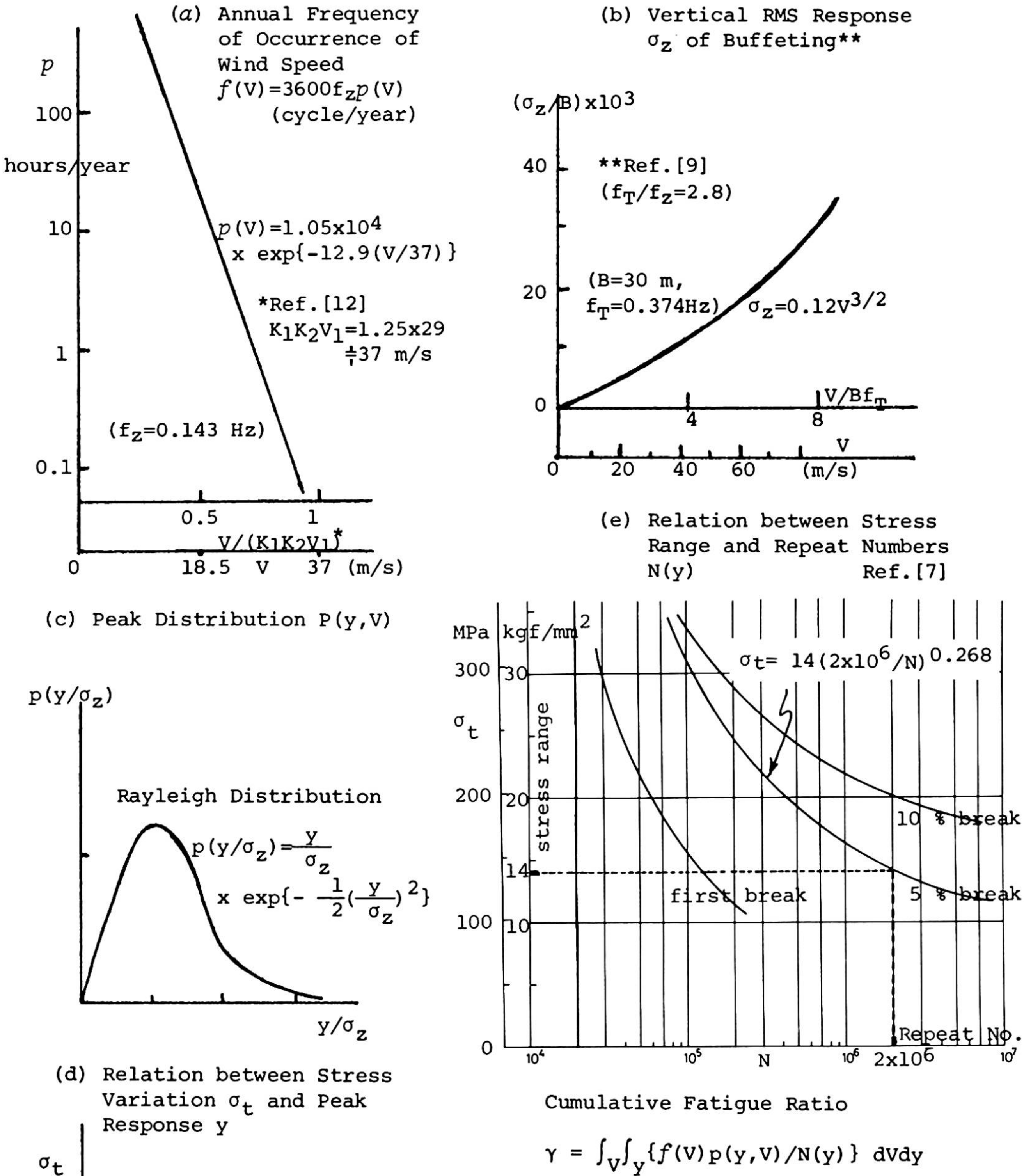


Fig. 3 Hanger Tension Distribution by Vertical Loading of Inertia Force with 1st Symmetric Mode Shape of Amplitude A=90 cm at Span Center Point



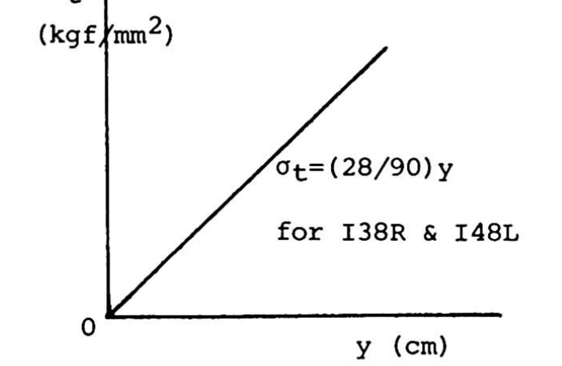


Fig. 4 Cumulative Fatigue Damage Ratio Calculation Flow Description

5. CONCLUDING REMARKS

Under longitudinal or vertical loadings, the tensile force variations in inclined and vertical hangers were analysed, and the estimations of fatigue damage were made taking account of their higher stress variations. Knowledge obtained is as follows ;

(1) The tensile force variations in the inclined hangers are essentially higher in a wider range, particularly in the shorter hangers, compared with those in the traditional vertical hangers, except two extreme end ones.

(2) The longitudinal load resulting from traction or braking of heavy vehicles may be one of important factors to cause the fast deterioration by fatigue. The wind-induced buffeting oscillations may result in a significant contribution to cumulative fatigue damage as well.

(3) As another factor to cumulate the fatigue deterioration, the vertical loading by far heavy vehicles arrangement assumed in 3.2, may be also significant, considering the results of the higher stress range occurred in the analysis in 4. and the studies described in Ref.[13,14].

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