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Curved Steel Guideway for Suspended Monorail System

Coulisse de guidage courbe en acier destinée à un système de monorail suspendu

Gekrümmte Stahl-Führungsschiene für ein schwebendes Einschienenbahn-System

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SUMMARY
A thin-walled steel beam with open cross-section, which is extremely weak in torsion, is used as the guideway for a rubber-tyred suspended monorail system. In order to understand clearly the behaviour of this special structure, both static and fatigue tests were carried out upon the half-scale model of an actual curved guideway beam.

RESUME
Une poutrelle d'acier à paroi mince et section transversale ouverte, de rigidité à la torsion extrêmement faible, sert de coulisse de guidage pour un système de monorail suspendu à pneu en caoutchouc. Des essais de charge et de fatigue ont été pratiqués sur un modèle à l'échelle 1/2 d'une coulisse de guidage courbe réelle dans le but de comprendre clairement le comportement de cette structure particulière.

ZUSAMMENFASSUNG
Ein dünnwandiger Stahlträger mit offenem Querschnitt, welcher extrem torsionsweich ist, wird als Führungsschiene für ein gummibandagiertes, schwebendes Einschienenbahn-System verwendet. Um das Betriebsverhalten dieser speziellen Struktur klar zu verstehen, wurden an einem Modell des gekrümmten Führungsschienenträgers (Massstab 1:2) Belastungs- und Dauertests durchgeführt.

1. STRUCTURAL DESCRIPTION

During the past several years increasing interest has developed in new forms of ground transportation which can provide automated high-capacity urban transportation. A number of advanced systems including personal rapid transit, dual mode, monorail and high speed ground system are under research and development in Japan. Chiba City, one of densely populated and highly industrialized cities in Tokyo metropolitan area, has recently decided to adopt a rubber-tired suspended monorail system as shown in Fig. 1. It is the first practical use of suspended monorail as a mass-transportation system in Japan. In the first stage of program it is planned to construct double track guideways of 17.5 kilometer length including twenty stations and terminals. One train is composed of four vehicles and the carrying capacity of this system becomes about 20 thousand passengers per hour. Since guideway cost usually far exceeds vehicle cost in this system, the technology of guideway design, construction and maintenance is extremely important. In Chiba monorail system thin-walled slender steel beams with large span are used as guideways, which can minimize aesthetic impact, required land area and construction cost. Silent and weather-proof operation is additional advantage in this system since runways, electric conductors and motor bogies are placed inside the guideway beams with box-type cross-section. We have, however, some unsolved technological problems about guideway design resulting mainly from existence of bottom split in the cross-section, which is necessary for passage of the pendulous suspenders connecting bogies to the vehicles.

Owing to this split the thin-walled guideway beams are of open cross-section, which is extremely weak in torsion and derives large warping stress. It influences the route-determination flexibility (permissible radius of curvature) because in the case of curved guideway beams large torsional moment arises from dead weight, vehicle loading, horizontal centrifugal force of running vehicle and wind force.

Typical cross-section of guideway in Chiba monorail is shown in Fig. 2. Only transverse stiffening frames of limited size are provided to prevent distortion

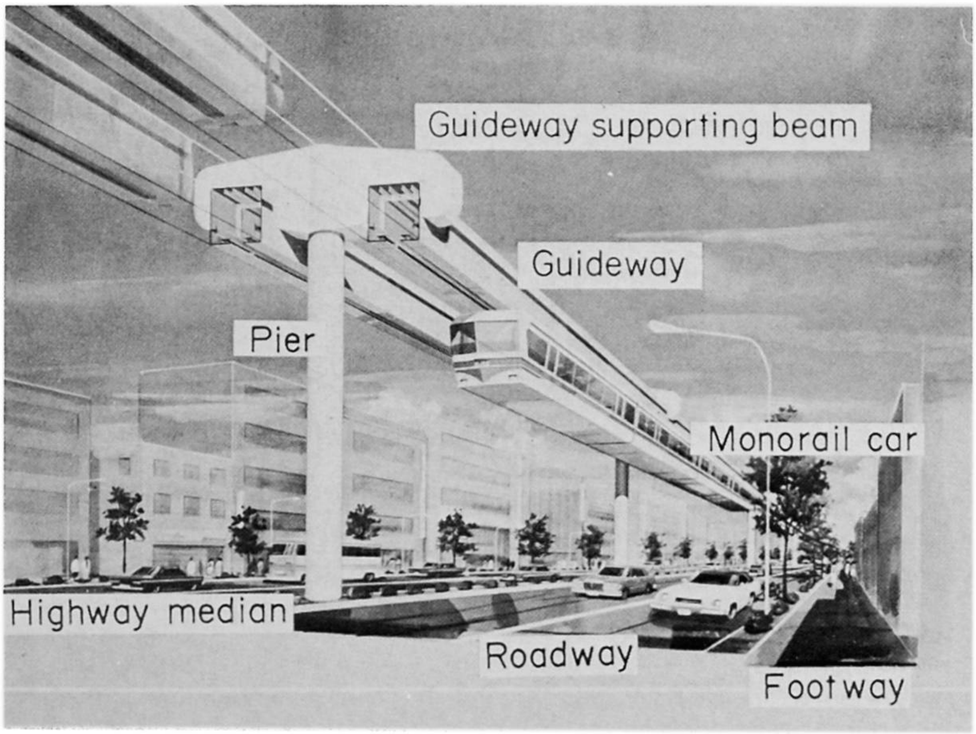

Fig. 1 Suspended monorail system

of the cross-section because it is impossible, in this special structure, to insert cross-bracings and lateral members for obtaining increased torsional stiffness.
Inevitable distortion of the cross-section will decrease the guideway stiffness and will induce additional stresses. The optimum size and spacing of the stiffening frame are therefore the most important factors considered in the guideway design. As the size and rigidity of runway beams are also limited, the local stress of runway beams beneath the wheel loads becomes another problem of consequence. In addition fatigue design of welded joints is very important in this structure since various initial imperfections can not be avoided in fabrication and serious local stresses are caused by repeated vehicle loads. In order to make clear the behavior of this special structure and to solve the above mentioned problems, both static and fatigue tests were carried out upon the half-scale model of an actual curved guideway beam.

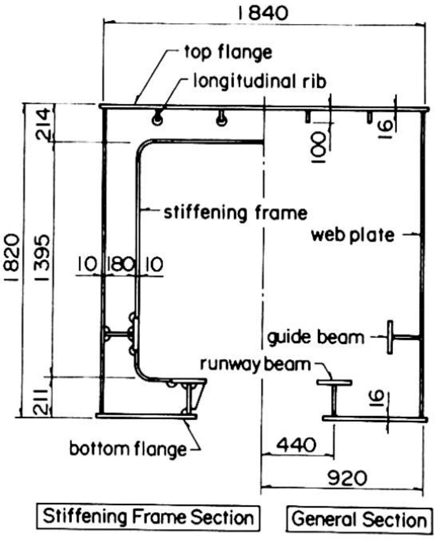

Fig. 2 Cross-section of guideway

2. EXPERIMENTAL MODEL, TESTING RIG AND INSTRUMENTATION

Dimensions of the simple span curved guideway model, which was used for both static and fatigue tests, are shown in Fig. 3. The model was fabricated from 9 mm thick steel plate (JIS-SS41) and transverse stiffening frames were positioned at regular intervals of 725 mm.
The static test was conducted under three different loading conditions, i.e., a vertical load divided into half point loads on the runway beams, a horizontal centrifugal load on outer guide beam and a horizontal centripetal load on inner guide beam. The maximum load applied in each test was chosen so that the stress of model did not exceed elastic limit.

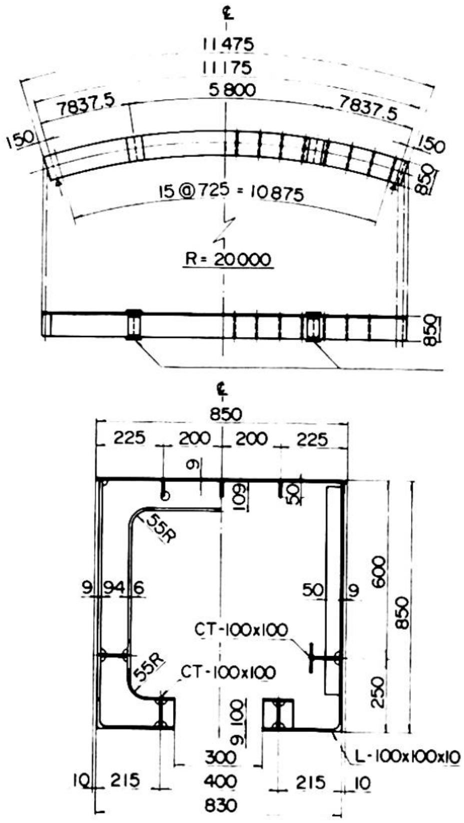

Fig. 3 Dimensions of guideway model (JIS-SS41)

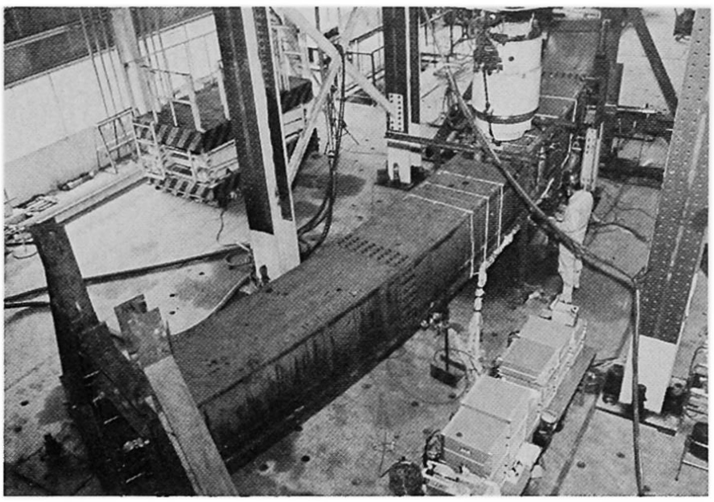

Fig. 4 General view of loading tests

The testing rig is shown in Fig. 4. The vertical jacking load was transmitted to the model through loading beam transversely placed on the parallel runway beams, whereas the horizontal jacking load through steel attachments welded to the outside of webs. The ends of the model were held within rigid restraining frames, which could be adjusted by means of steel rollers to provide both simple support condition and twisting restraint.
The instrumentation was arranged so that longitudinal and transverse stresses as well as displacements could be measured. About 400 electrical resistance strain gages were placed at various positions along the span. The strains were recorded by the automatic digital strain meters and the displacements were measured with 53 dial gages and 23 electric deflection meters.
The fatigue test was carried out by a 100-ton electro-hydraulic alternating testing machine under fluctuating bending with the same loading condition as the static vertical loading test.

3. STATIC TEST RESULTS

Since guideway cost may critically influence economic feasibility, reliable analytical techniques are needed in the design of guideway systems. Although the computer programs for the finite element method have already been developed, they are extremely expensive in practical use.
The conventional thin-walled beam theory, whether the axis of guideway is straight or curved, should be used for the basic design of the guideway beam having almost uniform cross-section, because it is able to concisely interprete overall structural behavior and is most economical. Local stresses due to the distortion of cross-section, however, have to be calculated by considering the interactions between the guideway skins and the stiffening frames. The most efficient modern method for analyzing such problem will be the finite strip method [1].
The finite strip method, however, does not permit to directly take into account the presence of transverse stiffening frames. To solve this problem the refined finite strip method [2][3] was used: the stiffening frame was represented as an assembly of finite elements. By using the flexibility matrixes of both the stiffening frames and unstiffened guideway beam, interaction forces between them were determined from compatibility equations. Finally the actual displacements and internal stresses in the whole structure were calculated.

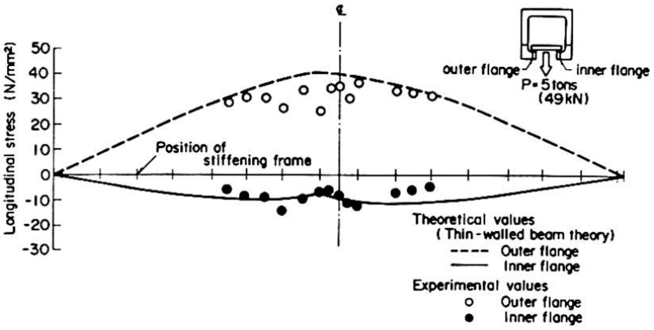

Fig. 5 Variation along span of longitudinal stresses in bottom flanges for a load applied at cross-section with stiffening frame

Both theoretical and experimental results have provided sufficient knowledges of guideway behavior, but herein a few typical results for vertical load of 5 tons (49 kN) are illustrated. In Fig. 5 the variation along the span of longitudinal stresses in the bottom flanges of parallel runway beams is plotted for a load applied at the section with the stiffening frame close to the mid-span. The corresponding distribution of longitudinal stresses at the mid-span cross-section is shown in Fig. 6. The measured stress values are in reasonably good agreement with those predicted by the thin-walled and curved beam theory.
The variation of longitudinal stresses at the same places as Fig. 5 for a load applied at the mid-span is plotted in Fig. 7. In this case the beam theory can not directly predict the local stresses induced in runway beams near the applied load, whereas the refined finite strip method can well explain

the local effect of the stiffening frames. The results indicate that it is possible, in the design of actual structures, to correct the stresses calculated from the thin-walled beam theory by adding the stresses of runway beams which are assumed to be multi-span continuous beams elastically supported by transverse stiffening frames.

In the case of horizontal loadings the general trend of stress distribution and effect of the stiffening frames were about the same for vertical ones, although the distortion of the cross-section was somewhat greater than that observed in the application of vertical loadings.

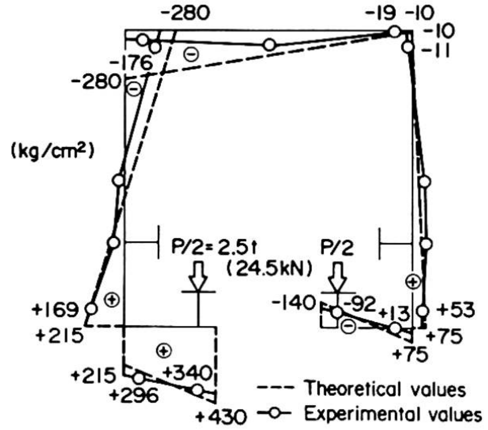

Fig. 6 Distribution of longitudinal stresses at mid-span cross-section

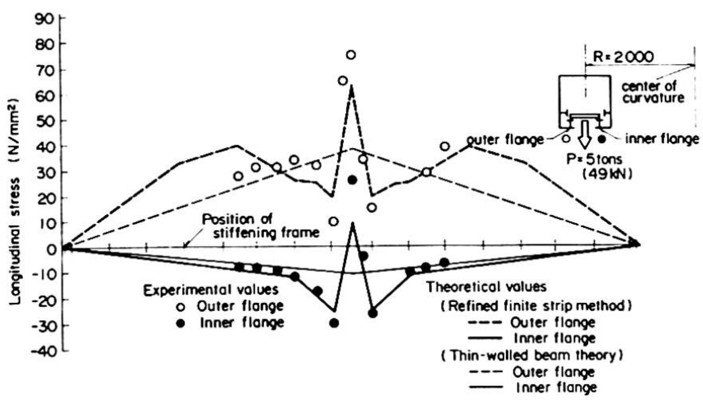

Fig. 7 Variation along span of longitudinal stresses in bottom flanges for a load applied at mid-span

4. FATIGUE TEST RESULTS

The stress range of 9.5 kg/mm^2 (93.1 N/mm^2) was given to the fiber of outer bottom flange by the applied minimum load of 2 tons (20 kN) and the maximum load of 9 tons (88kN) under the loading speed of 1.3 Hz.

The behavior of test beam under repeated bending was quite stable without any crack initiation up to 2.3 x 10^6 loading cycles and then the fatigue test at this stress range was completed. In fatigue design calculation of guideway beams, the stresses at welded joints of runway beams with adequately located transverse stiffeners, where the fatigue strength is the minimum among structural details of runway beams, should not exceed the fatigue strength of transverse non-load-carring fillet welded joints as shown in Fig. 8 [4].

Based on the linear cumulative fatigue damage rule, the equivalent number of cycles for design stress, N_{eq}, is represented with the experimental run-out fatigue life N_{test} as

$$N_{eq} = N_{test}(P_D/P_T)^m$$

where P_T, P_D and m denote the single-axle applied load range in fatigue test, the equivalent multi-axle wheel load range and the inclination of S-N curve respectively.

The ratio P_D/P_T can be calculated as 1.57 by the aforementioned refined finite strip method and m can be read as 3.0 in Fig. 8, then the fatigue life of guideway with such structural details as the experimental model is estimated at more than 8.9 x 10^6 cycles.

For the purpose of investigation about fatigue failure mode in this model, an additional load repetition test was carried out under loading conditions of the minimum load of 2 tons and the maximum load of 11 tons. As a result, a fatigue crack caused by stress concentration and weld defects was initiated at the frame corner and propagated into stiffening frame adjacent to loading point as shown in Fig. 9. The similar cracks were initiated at other stiffening frames one after another with the decrease of stiffening effects of frames due to crack propagations. From the results of another large-scaled guideway model tests, however, this kind of fatigue crack was proved to be avoided by perfoming full penetration without initial imperfection at flange butt welded joints or by separating the inner flanges of guide beams from stiffening frames.

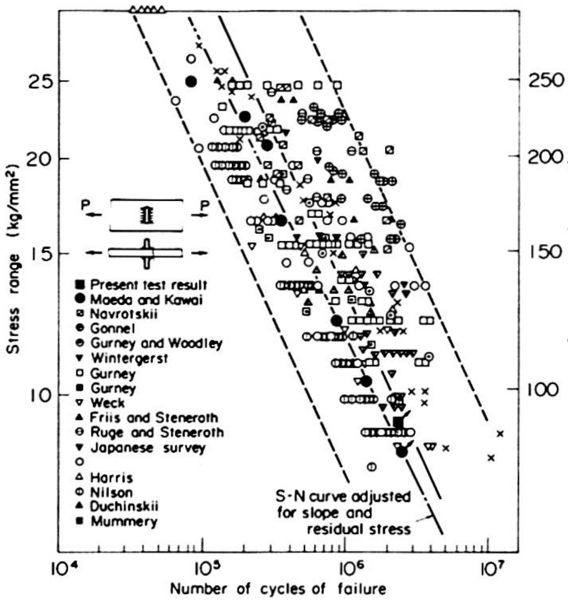

Fig. 8 S-N curve for transverse non-load-carrying fillet welded joints

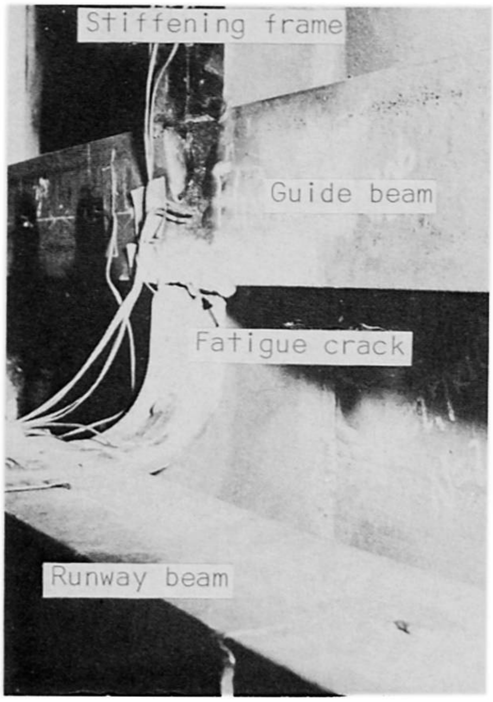

Fig. 9 Fatigue crack initiation at stiffening frame corner

5. CONCLUSION

Suspended monorail system will be one of attractive mass-transportation systems in urban areas from the view points of safety, carrying capacity, aesthetic impact, required land area, construction cost, maintenance, etc..

Guideway design for the suspended monorail must consider at least the factors of optimum size and spacing of the transverse stiffening frames, local stresses in bottom flanges beneath the wheel loads and guideway dynamics including fatigue strength.

The optimum size and spacing of stiffening frames are easily and economically determined by parametric studies using the refined finite strip method which is capable of providing an accurate representation of the behavior of guideway beams. Local stresses in bottom flanges can be predicted with reasonable accuracy by assuming runway beams to be multi-span continuous beams elastically supported by transverse stiffening frames.

From the test results, fatigue limit of guideway was estimated at more than 9.5 kg/mm^2.

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