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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 transpor-
tation. 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 influ-
ences 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
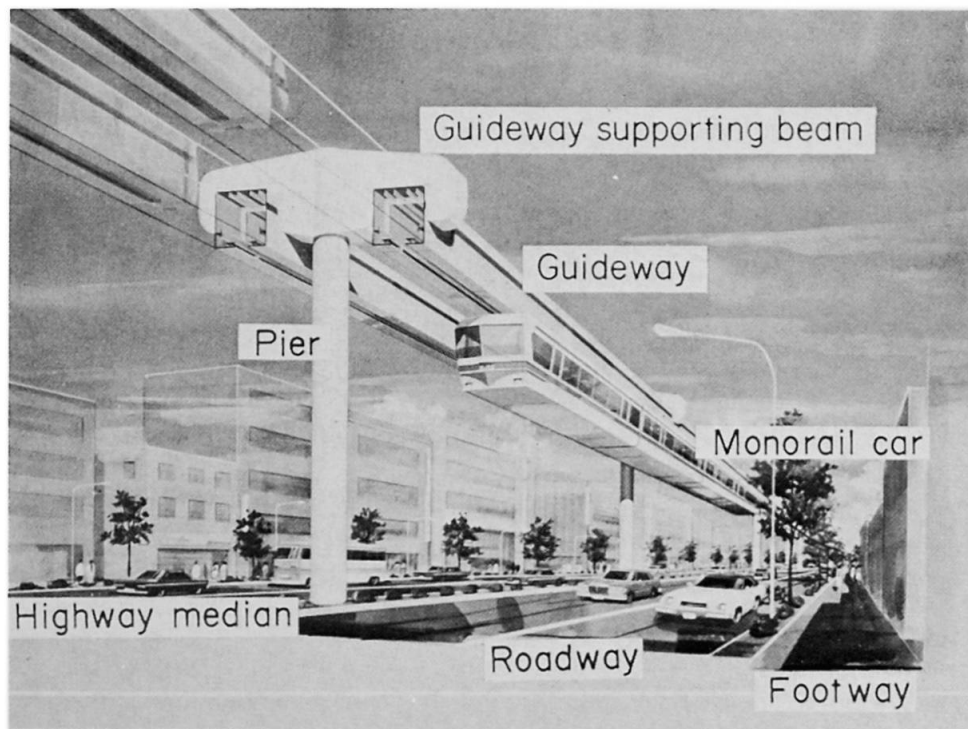transverse stiffening frames of limited size are provided to prevent distortion

Fig. I   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 spac-
ing 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 im-
portant in this structure since various initial
imperfections can not be avoided in fabri-
cation 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 differ-
ent 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
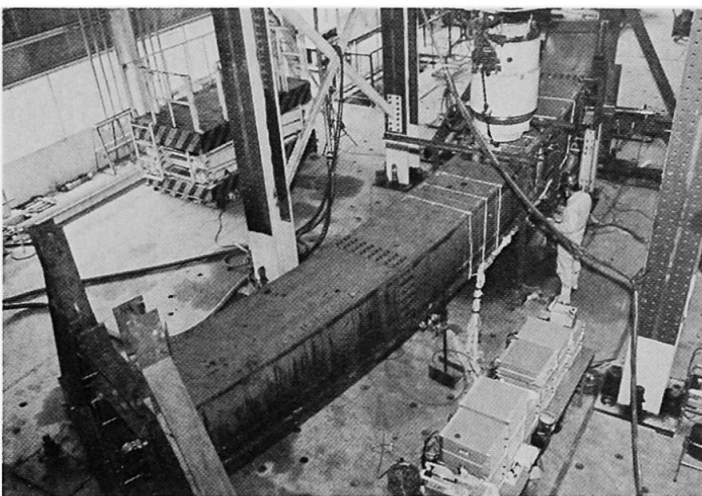elastic limit.
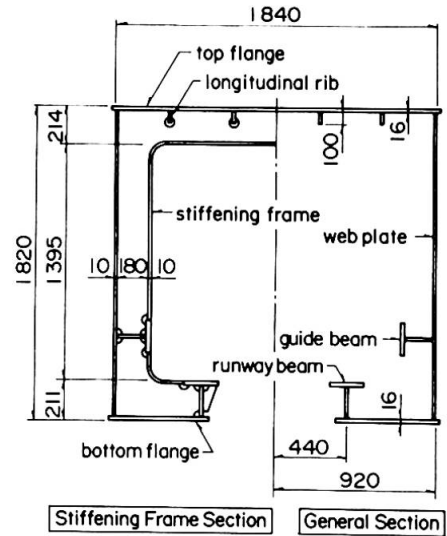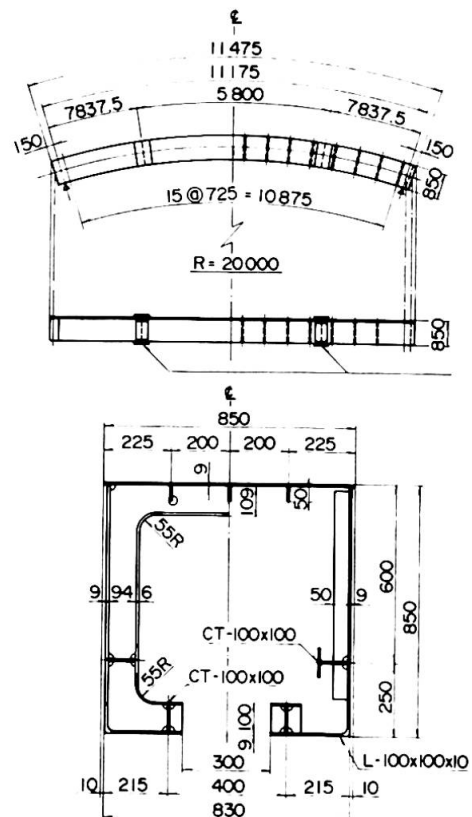

Fig. 4 General view of
loading tests

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

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 re-
corded 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 stiffen-
ing frame was represented as an
assembly of finite elements. By
using the flexibility matrixes of
both the stiffening frames and un-
stiffened guideway beam, interac-
tion forces between them were
determined from compatibility

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

equations. Finally the actual displacements and internal stresses in the whole
structure were calculated.
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
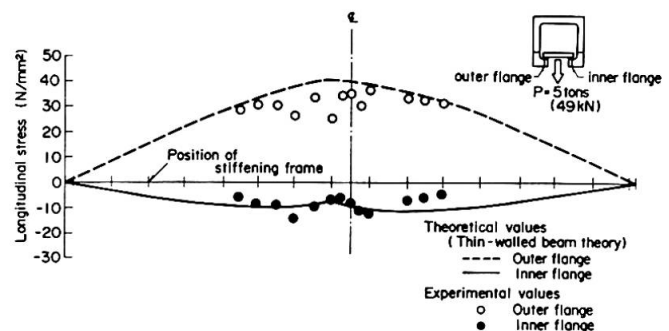applied load, whereas the refined finite strip method can well explain

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.
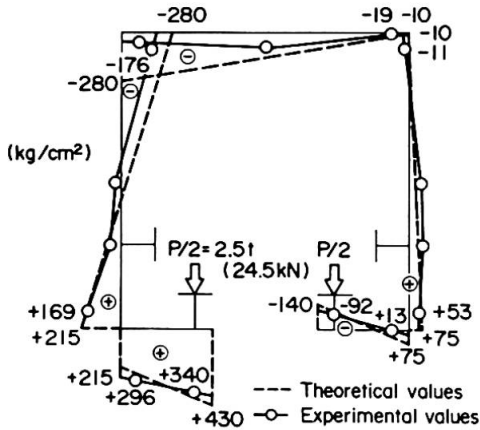

Fig. 6 Distribution of longi-
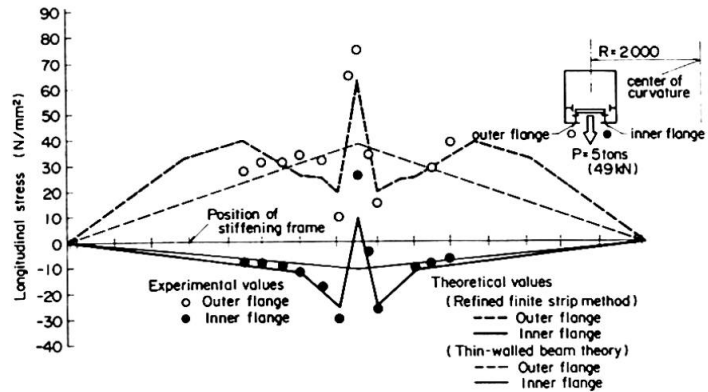tudinal stresses at mid-span
cross-section

Fig. 7 Variation along span of longi-
tudinal 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 2.3×10^6 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 8.9×10^6 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.
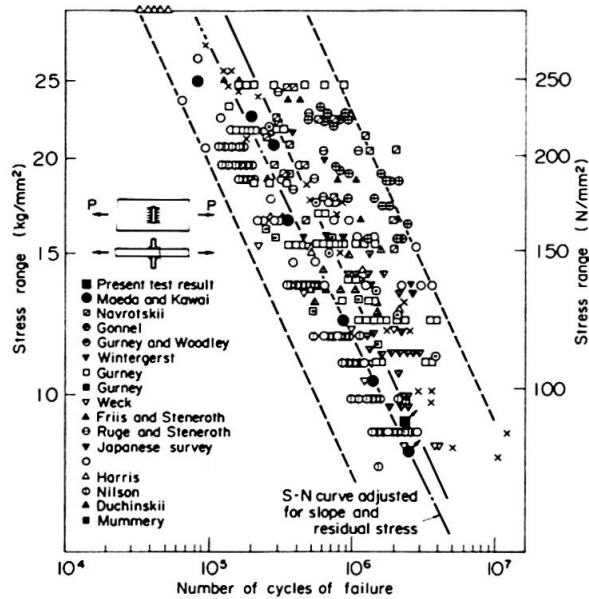
Fig. 8 S-N curve for transverse non-load-carrying fillet welded joints
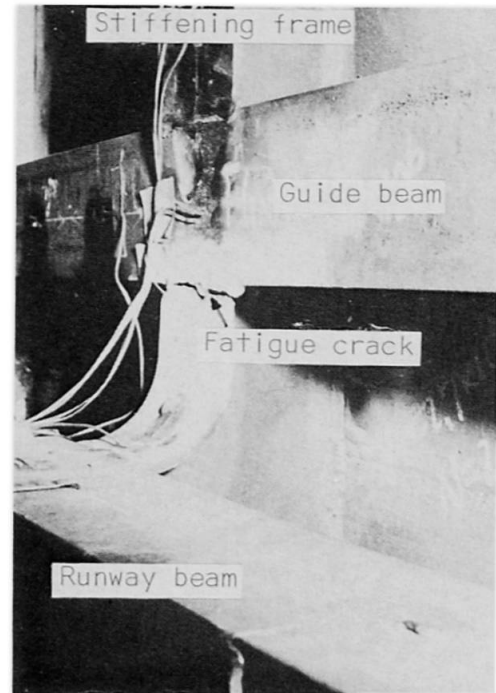
Fig. 9 Fatigue crack initiation at stiffening frame corner

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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