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Seismic Response of the Tagus River Bridge, Portugal

Comportement du Pont sur le Tage, Portugal, vis-à-vis des séismes

Seismisches Verhalten der Tagus-Brücke in Portugal

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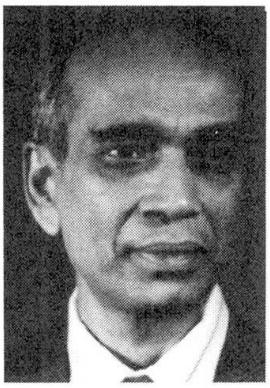

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SUMMARY

To carry the railroad over the Tagus River Bridge in Portugal, the design strengthens the existing bridge with a second cable system. In the original design, the bridge was evaluated for seismic design criteria significantly different from those used today. This paper outlines the present analysis procedure and the seismic response of the modified Tagus River Bridge.

RÉSUMÉ

Afin de pouvoir supporter le trafic ferroviaire, le projet prévoit le renforcement du pont sur le Tage avec un deuxième système de câbles. Dans le projet original, le pont avait été calculé pour des forces sismiques assez différentes des valeurs retenues actuellement. L'article présente la méthode actuelle de calcul et le comportement du pont modifié vis-à-vis des séismes.

ZUSAMMENFASSUNG

Zur Überführung einer neuen Eisenbahnlinie über die Tagus-Brücke verstärkte der neue Entwurf die damalige Brücke mit einem zweiten Kabelsystem. Die seismischen Kriterien des neuen Entwurfs unterscheiden sich stark von den alten Anforderungen. Der Artikel fasst die neuen Rechnungsverfahren und das seismische Verhalten der modifizierten Tagus-Brücke zusammen.

1. INTRODUCTION

In 1992 Junta Autonoma de Estradas (JAE) of Portugal awarded a design contract to Steinman, Inc, New York for the installation of a new railroad deck on the suspension bridge over the Tagus River in Lisbon. The contract also calls for the widening of the existing upper roadway deck from five to six lanes.

Tagus River Bridge, designed by Steinman for the US Steel Export Company, was opened to vehicular traffic in 1966. The suspended spans of the Tagus River Bridge are 483 m, 1013 m and 483 m. The stiffening truss is 2271 m long and continuous throughout the suspended spans and three backstay spans.

To carry the railroad, Steinman's design strengthens the existing bridge with a second cable system supported at new anchorages and extensions to the existing towers and bents. The new lower deck, designed to carry the railroad, will be an orthotropic system of new floorbeams, laterals and railway stringers, all of which will participate with the existing truss bottom chords. Construction is scheduled for 1995-1998. Fig.1 shows the proposed bridge elevation and cross section.

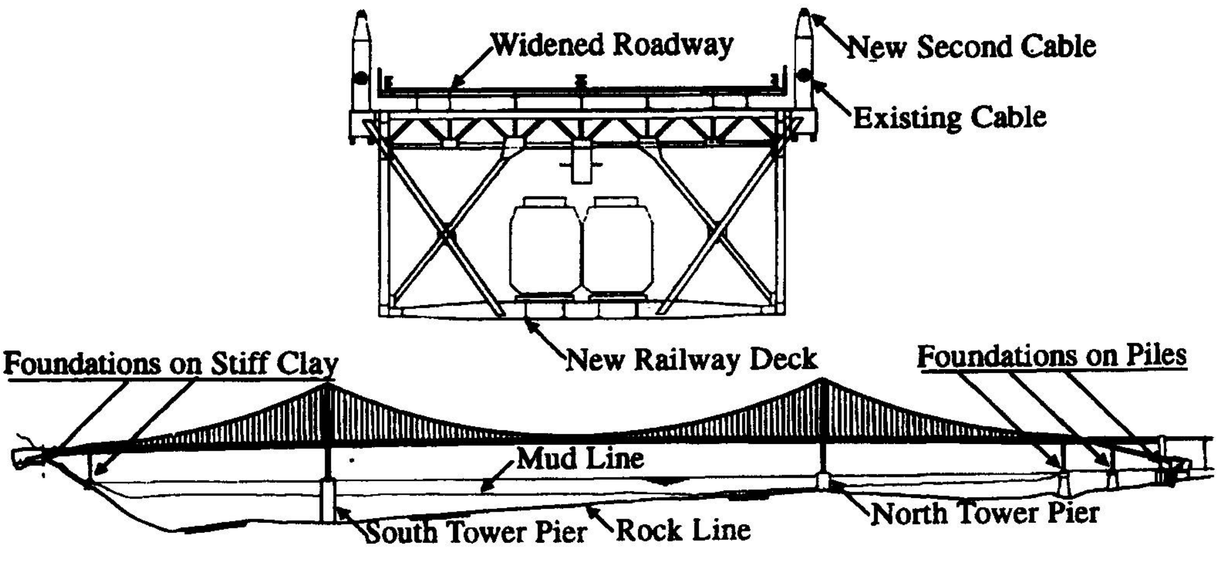

Fig. 1: Tagus River Bridge Elevation and Cross Section

2. SEISMIC ACTIONS

In 1961, seismic action was quantified as 10% of the dead load acting either in the longitudinal or transverse direction. The present Portuguese Code, RSA, characterizes Seismic actions by Response Spectrum with 5% damping (Fig. 2). Due to the importance of the structure, Steinman engaged Prof. George Gazetas, a soil-structure-dynamics expert, to provide realistic support excitation data and support spring constants for the Tagus River Bridge. Prof. Gazetas in association with a team of experts (Prof. M.K. Yegian, Prof. P. Dakoulas, Dr. V.G. Ghahraman, Dr. H. Abou-Seed, Mr. G. Mylonakis and Ms. A. Nikolau) studied the site seismicity and soil data. They recommended the following:

1. A 15 second seismic action with a peak acceleration (PGA) of 0.25g at the rock level. This seismic action (NEAR EQ) is assumed to originate at a nearby source and has an estimated return period of 200 years. NEAR EQ must not damage the structure.
2. A 55 second 0.15g PGA seismic activity originating at a distant source (DISTANT EQ) with an estimated return period of 2000 years. The structure may undergo repairable damage during DISTANT EQ.

A thorough soil-structure interaction study was undertaken. Using a strain-compatible soil profile, a free-field soil seismic response analysis of a multi-layered soil column was performed. The seismic responses of the tower caissons (partly embedded in soil) were obtained from finite element models of the soil-structure system. The caissons were modeled as three dimensional solid elements. The surrounding soil was modeled without artificial lateral boundaries. Hydrodynamic masses and the flexibility of the bedrock were considered. The soil-structure interaction study provided the following information for NEAR EQ and DISTANT EQ in the longitudinal and transverse directions:

1. Time histories of accelerations at the base of the towers, bents and anchorages (See Fig. 3 for typical examples).
2. Translational and rotational spring constants for the base of the towers, bents and anchorages.

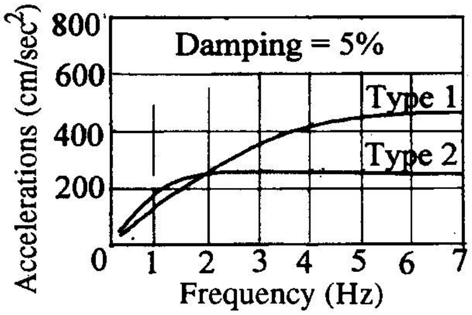

Fig.2: RSA Response Spectra

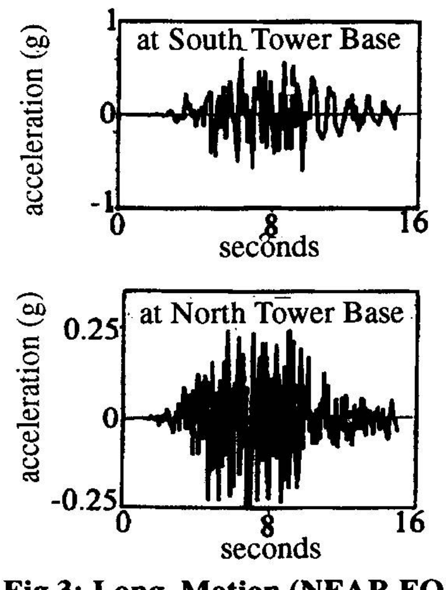

Fig.3: Long. Motion (NEAR EQ)

3. ANALYSIS PROCEDURE

Determination of the seismic response corresponding to the original 1961 design criteria is a simple static analysis problem. Seismic actions characterized by RSA spectra require a standard spectral analysis. Steinman's seismic action criteria using different support excitations demand an elaborate and time consuming time-history integration (See Table 1).

Analysis	Seismic Action	Mass Excitation	Duration	Integration Time Step
Time-history:	NEAR EQ	Longitudinal	15 sec	0.125 sec
	NEAR EQ	Transverse	15 sec	0.125 sec
	DISTANT EQ	Longitudinal	55 sec	0.250 sec
	DISTANT EQ	Transverse	55 sec	0.250 sec
Spectral	RSA: Type 1	Longitudinal		
	RSA: Type 1	Transverse		
	RSA: Type 2	Longitudinal		
	RSA: Type 2	Transverse		
1961 Style	10% of DL	Longitudinal		
(Static)	10% of DL	Transverse		

Table 1: Seismic Analysis of the Tagus River Bridge

An in-house computer program, developed by the primary author, was used for all of the design and analysis phases. The program uses standard matrix methods for non-linear structural analysis. The DYNAMICS module of the program computes mode shapes and frequencies, and performs standard spectral analysis. For the time-history analysis, the program module uses Newmark's step-by-step direct integration method and computes the response of the structure due to a given time-dependent load $\{F_t\}$ by solving the basic dynamic equilibrium equation:

$$[M]\{U''\} + [C]\{U'\} + [K]\{U\} = F_t$$

Before proceeding with time-history integration, the following items needed clarification:

1. Integration Time Step
2. Different Support Excitations
3. Quasi-Static Stresses due to Support Displacements
4. Computer Model

3.1 Integration Time Step

Ordinarily, one tenth of the period of the significant lowest mode of the structure is taken as the integration time step. The fundamental periods of the structure in the longitudinal and transverse directions are 5.76 seconds and 15.03 seconds respectively. The integration time steps indicated in Table 1 are much less than one twentieth of the fundamental period. To establish integration time steps, plots of spectral accelerations were generated by integrating the support motions (Fig. 3) at 0.02, 0.04, 0.125, 0.25 and 0.5 second time steps. The chosen integration time steps yielded response spectra almost identical to those with much smaller time steps. This was particularly true within the range of the important lowest few frequencies of the structure. The maximum stress obtained with the integration time steps in Table 1 is 88% of the yield stress. A smaller time step at the cost of substantial computational effort may have produced slightly higher stresses without significantly impacting the results.

3.2 Different Support Base Excitations

The in-house computer program uses time-dependent load vector F_t to account for the different support base excitations. For each earthquake, time-dependent load vectors were generated for every joint in the computer model. In other words, the structure was analyzed for time-dependent joint loads.

At any time, t, load F_j at joint j was taken as

$F_j = M_j \sum\delta_{kj} U''_k$ where

M_j = mass at joint j
δ_{kj} = displacement of joint j due to a unit displacement of support k while all the other supports are immovable.
δ is assumed to vary linearly between support k and the adjacent support.
U''_k = acceleration of support k.
The summation applies to all supports.

3.3 Quasi-Static Stresses due to Support Displacements

The quasi-static stresses in the structure are the stresses due to the support displacements corresponding to time t. If all of the support displacements at any time, t, are the same, the structure experiences only a rigid body motion and there are no quasi-static stresses. From the soil-structure interaction study, the maximum quasi-static displacements of 0.15 m and 0.05 m occur at the base of south and north towers respectively. Member stresses due to these maximum displacements were found to be less than 5% of the member yield strength. Compared to the tower heights, the quasi-static displacements are very small, and thus were ignored from further consideration.

3.4 Computer Model

In time-history integration, the structure is analyzed independently for every time step. For 55 seconds of seismic action with an integration time step of 0.25 second, 220 independent analyses are required. To minimize the computational effort, a simplified 3D model of the Tagus River Bridge was used for the seismic analysis. The bridge was idealized as a space frame with 482 joints and 1000 members. The stiffening trusses were modeled with equivalent beams supported by half the actual number of suspenders. The bents and towers in the model were supported on springs. The lowest significant mode shapes and frequencies of the seismic model were compared with the corresponding values obtained from a more elaborate 3D model of the bridge composed of 3062 joints and 7044 members. The mode shapes from the two models were identical, while the difference in the corresponding frequencies was less than 2 percent.

4. RESULTS

The time-history analysis was carried out for NEAR EQ and DISTANT EQ, with separate analyses for longitudinal and transverse directions (See Table 1). Typical examples of deformations and member stresses are given in Fig.4 and Fig. 5.

The stresses in the bents and towers due to the seismic excitations included in this study did not exceed the yield stress. The south tower was found to experience tension at the base during DISTANT EQ acting in the longitudinal direction (Fig. 5). The corresponding south tower anchor bolt tension is approximately 69 N/mm^2. The south tower has a long caisson through mud and thus reacts unfavorably to seismic actions. However, considering the return period of DISTANT EQ and the low magnitude of the south tower tensions the situation was not considered of great concern. No such tension in the towers occurred due to the NEAR EQ.

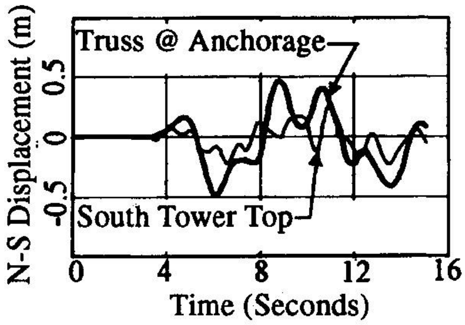

Fig. 4: System Response (NEAR EQ @ N-S)

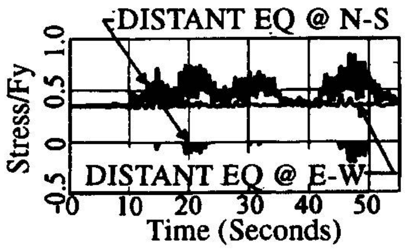

Fig. 5:South Tower Bottom Stresses

Many bridge failures are due to spans slipping from their supports during intense seismic actions. In the Tagus River Bridge, the truss roller movements at the anchorages due to seismic actions were found to be less than the movements due to live load and temperature. Furthermore, the existing bridge is equipped with restraints to limit the roller movements at the anchorages.

A comparison of the results from the various analyses identified in Table 1 found that the RSA Spectral Analysis under-estimated both the deformations and member stresses obtained from the time-history analysis, while the 1961 style equivalent static analysis grossly overestimated the deformations and underestimated the tower and bent stresses. The reconstructed Tagus River Bridge is capable of resisting stresses obtained from all the three types of seismic analysis.

5. ACKNOWLEDGMENTS

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