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A Modular Steel Freeway Bridge: Design Concept and Earthquake Resistance

W. H. Wattenburg, D. B. McCallen, R. C. Murray

A modular multilane steel freeway bridge has been constructed from surplus railroad flatcar decks. It can be erected on-site in a few days' time. It has been built and static-load tested for emergency freeway bridge repair. This inexpensive modular bridge may also have broad application around the world for low-cost bridges in areas where funds are limited. On the basis of static-load testing performed by the California Department of Transportation and computer dynamic analysis, this simple modular-design concept has the potential of providing a strong bridge that can withstand the severe aftershocks expected immediately after a major earthquake.

A modular steel, multilane freeway bridge was constructed and evaluated in March 1994 by the California Department of Transportation (Caltrans) as a temporary bridge for emergency freeway repair. It can be erected on-site within a few days' time without extensive site preparation or ground disturbance to restore traffic over damaged freeway sections such as those that collapsed in the 1994 Northridge earthquake and the recent Hyogo-Ken Nanbu earthquake in Japan. Because of its potential importance for emergency response and other infrastructure uses described herein, we independently performed a computer dynamic analysis of a model of the bridge at the Lawrence Livermore National Laboratory to investigate its earthquake response characteristics.

W. H. Wattenburg, University Foundation, California State University, Chico, CA 95929, USA.
D. B. McCallen, Structural Mechanics Group, Lawrence Livermore National Laboratory, Livermore, CA 94550, USA.
R. C. Murray, Geologic and Atmospheric Hazards, Lawrence Livermore National Laboratory, Livermore, CA 94550, USA.

The modular bridge design was first proposed by Wattenburg (*1*) and constructed by Caltrans (Fig. 1). The as-built modular bridge uses only one standard structural module: inexpensive surplus railroad flatcar decks. However, structurally equivalent modules can be constructed from ordinary steel I-beams. This design has its own base support for the column structures (bents) and requires only simple steel fasteners. This modular bridge costs relatively little compared to other steel and reinforced or prestressed concrete freeway bridges, which cost three to five times as much and require months to construct.

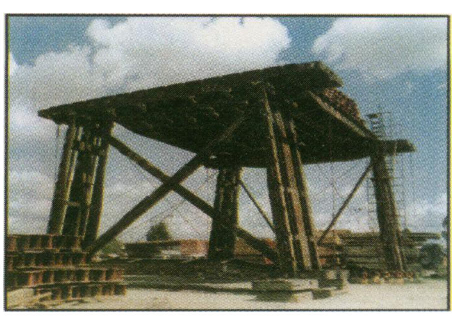

Fig. 1. Prototype module constructed for the California Department of Transportation.

The modular bridge constructed by Caltrans is shown in Fig. 2. The individual 3 m wide by 16 m long flatcar modules (Fig. 2A) are massive steel frame structures that are designed to carry loads of up to 50 metric tons. The flatcar modules are coupled together in interlocked fashion such that the module connections emulate pinned joints (Fig. 2B). The 15-m-wide roadway deck of the assembled bridge consists of four flatcars side-by-side, which span 16 m between two vertical piers (Fig. 2C). The piers are constructed with a single flatcar in the horizontal direction (on top) supported by two half-flatcar vertical columns. The pier structure provides its own foundation with a horizontally placed flatcar on the ground at the foot of each pier. In the transverse direction, two diagonal steel braces are added to provide stability and stiffness to the assembled pier structure. Strong surplus boxcar center beams are used for the diagonal braces. In the longitudinal direction, the underside of the bridge is left open without obstruction to allow for passage of traffic from cross streets or railroads spanned by the bridge.

Vertical steel cables are used to constrain the top and bottom horizontal modules of the piers so that the vertical columns between them cannot come out of their joint sockets in the horizontal modules. The four adjoining flatcars on the top, which form the bridge roadway, are coupled together side-by-side by inserting simple U-bolt brackets into matching stake slots on the side of each flatcar deck (Fig. 2).

Ten surplus railroad flatcars were required for the bridge shown in Fig. 1. The Caltrans prototype was erected in 10 days by a construction crew of four, utilizing one 22.7–metric ton–capacity crane. The interconnection of the flatcars was accomplished in "Lego-block" fashion (*2*) to minimize the need for special brackets and to reduce assembly time. The ends of the vertical column flatcar modules are cut in a configuration such that their beam ends project into and around the support beams of the horizontal modules above and below.

Caltrans tested the as-built modular bridge with a static load of ~110 metric tons at center span. The observed vertical deflection was only ~0.3 cm under this heavy loading. We decided to analyze the stand-alone, 16-m-long bridge section shown in Fig. 1 for its ability to withstand significant seismic ground motion, in par-

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ticular, earthquake aftershocks. Reasenberg and Jones (3–5) have studied the aftershock sequences from a number of California earthquakes and the hazards associated with the earthquake aftershocks. In the first week after the main event, there is approximately a 60% chance of a large aftershock and a 10% chance of an even larger event. If a temporary bridge is immediately erected to replace a damaged bridge, say on the first day or two after an earthquake, it is quite likely that it will be subjected to a significant aftershock within the first week.

We constructed a finite-element model of this modular bridge for computer analysis (Fig. 3). The finite-element model discretizes the structure into a number of small or "finite" elements, and the stiffness behavior of each element is mathematically defined. By appropriate summation of the elements to form the overall structure, a system of coupled simultaneous equations are formed that, when solved, provide a time history of the displacements, velocities, and accelerations of the structure. Forces and stresses in the individual structural elements are then obtained from the displacements. For the finite-element model in Fig. 3, the system of equations defining the dynamic motion of the structures contained 7880 equations.

To ensure that the ground motion used in the seismic analysis of the modular bridge was representative of a significant aftershock, we applied the measured ground motion from the April 1992 Petrolia–Cape Mendocino earthquake. The records were obtained from the California Division of Mines and Geology strong-motion instrumentation array at the Painter Street Overcrossing site in Rio Dell, California (6). The north-south component of motion at this site was quite strong with maximum accelerations equal to 0.55 times the acceleration of gravity (0.55g). It was felt that these records would be representative of ground motion from a strong aftershock at close proximity to an earthquake epicenter. We applied simultaneous three-component motion to the bridge model where both horizontal components of motion are defined by the north-south component of the Petrolia earthquake record. In typical bridge structures, the bridge superstructure is supported by the abutments when the deck starts to rock back and forth during seismic shaking. However, this bridge, when used as a temporary freeway bridge, typically will not have strong abutment support during the time it is being erected, and it will likely be loosely coupled to existing freeway structures for some time after erection (Fig. 4). Thus, this temporary bridge must be self-sufficient in its ability to withstand the forces generated by earthquake ground motion. To reflect this in the computer simulation, the bridge model in

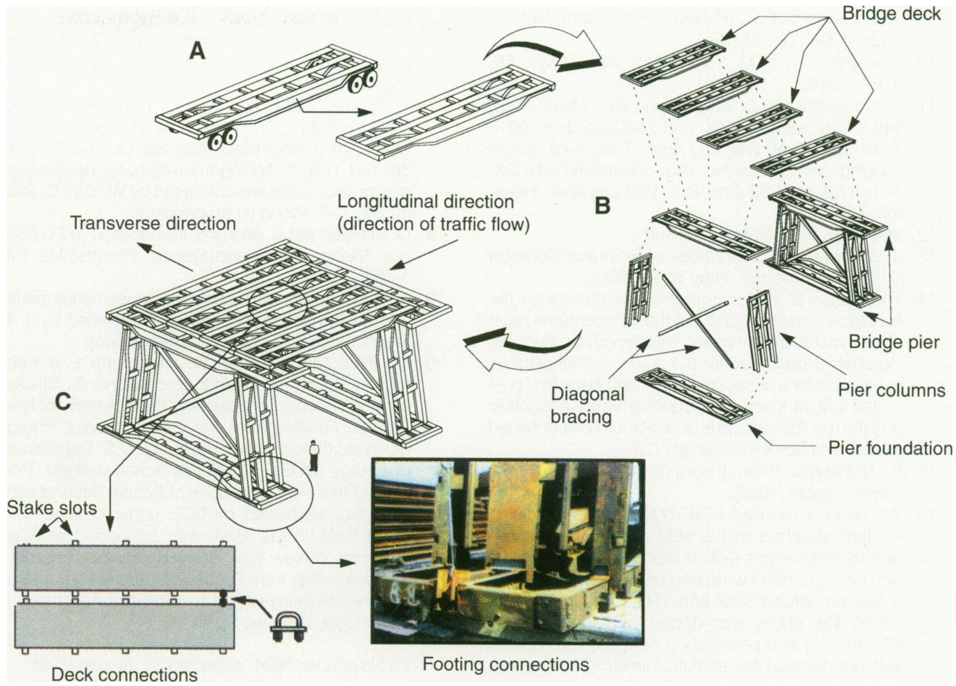

Fig. 2. Assembly of a bridge module with the use of surplus railroad flatcars.

Fig. 3 was assumed to stand alone, and the bases of the pier columns were assumed to behave as pin connections.

In our model, the bridge behaves as a truss structure in the lateral direction because of the diagonal braces in each column structure (Fig. 3). Because traffic must flow under the bridge, diagonal bracing is not used in the longitudinal direction between columns. Thus, the structure acts as a frame in the longitudinal direction with stiffness provided by bending of the columns. In addition to the weight of the structure, a weight of ~35 metric tons was added to the deck to account for the potential weight of vehicles and decking material. To reflect the as-built condition of the Caltrans bridge, the connections of all structural members were assumed to be pin connections. For analysis purposes, the damping of the structure was assumed to be 5% critical damping in the first few modes of vibration. The computer

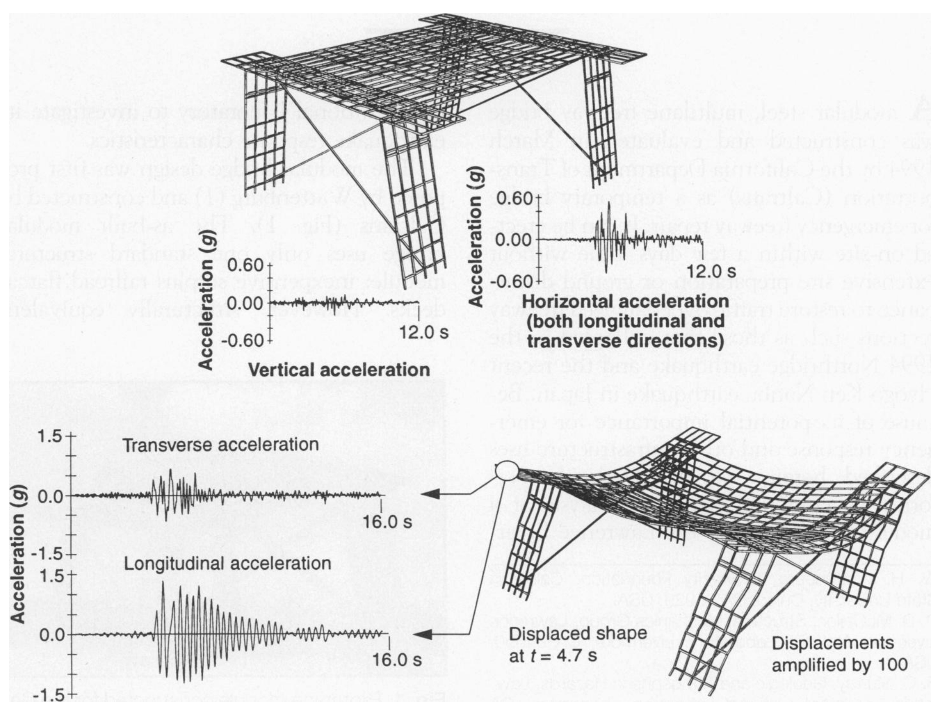

Fig. 3. Computer model of the bridge module.

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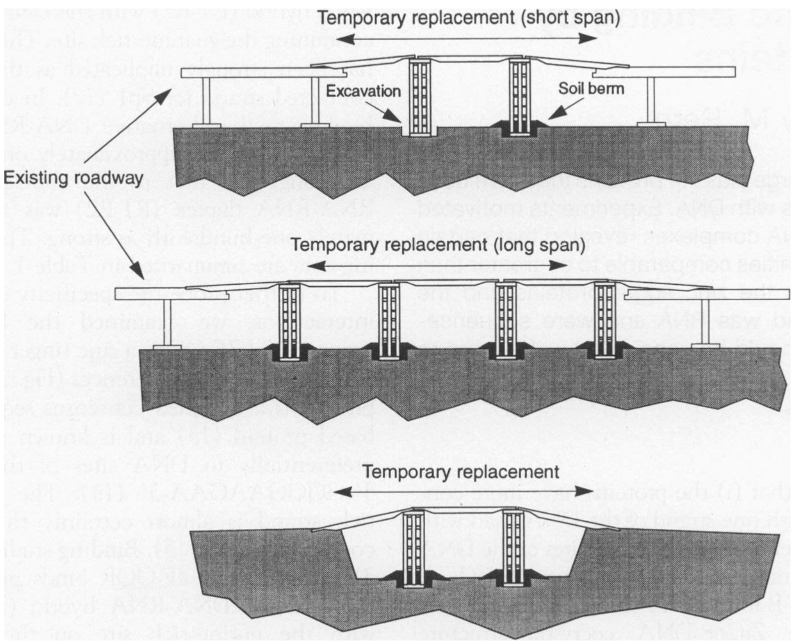

Fig. 4. Temporary bridge construction with the portable modules.

simulation of the seismic response of the bridge structure consisted of a direct-integration time history solution in which the response of the structure was calculated every 0.02 s of the 20-s earthquake record for a total of 1000 time steps. The actual computation was performed with the NIKE3D (7) finite-element program on a Cray YMP computer.

The seismic response of the bridge section at a selected instant of time is shown in Fig. 3 (displacements amplified by 100), along with the acceleration time history at the top of the structure. With the diagonal bracing, the structure is quite stiff in the transverse direction, and there is little amplification of the ground motion at deck level. In the longitudinal direction, the accelerations at the top of the structure are greater than 1*g*. Thus, significant amplification of the ground motion occurred. However, a check of column and diagonal member stresses from the seismic analysis indicated that the stress levels in the massive steel members were below allowable yield stresses (that is, the stress levels at which permanent deformation of the material commences). Although this analysis did not address the integrity of the structural joints, the computer simulation does indicate that the main structural members have significant strength to resist earthquake-induced forces. Caltrans has stated that the module joints formed by interlaced beams (Fig. 2) as used in their modular bridge will support the development of the full strength of the structural modules.

Previous computer simulation work with existing short-span overcrossings (8) allowed a comparison of the dynamic characteristics of this modular bridge with those of an actual short-span bridge, the Painter Street Overcrossing in Rio Dell, California. The frequencies of the modular bridge are in the same frequency range as the frequencies of the overcrossing. Thus, the fundamental dynamic characteristics of the stand-alone modular bridge section are not unlike the dynamic characteristics of typical permanent bridge structures.

Both the measured and computed transverse deck accelerations for the Painter Street Overcrossing in the 1992 Petrolia–Cape Mendocino earthquake were on the order of 1*g*. This is close to the computed accelerations for the modular bridge (Fig. 3). The primary difference between the dynamic responses is that the stand-alone modular bridge, not being attached to embankments, tends to vibrate longer because it has less inherent damping than the Painter Street bridge. The typical permanent bridge benefits from high damping as a result of energy dissipation in the embankment soils to which it is attached.

Surplus flatcars are an abundant source of strong steel modules with structural features that allow easy connection to make a modular bridge. The computer model we have analyzed herein uses simplified structural modules that represent only the main beams and cross supports found in the typical flatcar design. The simple modules in our model can easily be built out of standard I-beam material (for example, surplus steel I-beams), should an agency want to build this bridge without the use of flatcars.

The static-load testing performed by Caltrans and the computer dynamic analysis indicate that this conceptual modular bridge has the potential to withstand significant earthquake ground motion. This conceptual design provides a basis for a temporary bridge structure that can be erected quickly after an earthquake, and this could substantially enhance the postearthquake response of transportation agencies. The static and dynamic test results indicate that this inexpensive modular bridge could also be used for permanent bridges in many areas where funds are not available for bridges of current design. Modular steel bridge structures in general could capitalize on the economies of design and construction available from mass production of bridge components. The concept of prefabrication has become ingrained in the process of building construction in the United States, and extension to the bridge community seems inevitable. A permanent modular steel bridge concept has recently been proposed (9) that would utilize interconnection of modular steel bridge segments for essentially the entire bridge.

Many underdeveloped countries lack critical transportation facilities. There is a large amount of surplus steel I-beam material in the world that could be used to build this modular bridge if surplus flatcars are not available. Surplus steel beams are usually as structurally strong as new material. Building steel modules adequate for this bridge design requires little skill other than cutting and welding the steel beams together. Underdeveloped countries could build versions of this modular bridge to provide vital transportation for their people long before they can afford the elegantly designed concrete or other steel bridges to which those in developed nations are accustomed. Furthermore, this modular bridge can be erected and relocated relatively easily by communities that do not have extensive bridge design and construction capability.

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