The Nimitz Freeway Collapse

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One of the most tragic sights created by the Loma Prieta earthquake of Oct. 17, 1989, was the collapse of the double-deck Nimitz Freeway (the Cypress Street Viaduct on Interstate 880) just south and east of the San Francisco-Oakland Bay Bridge in Oakland. Along a 1.4-km north-south stretch, the upper deck of the freeway fell on top of the lower deck of the freeway, killing 42 motorists (see Fig. 1). Even though the earthquake occurred during rush hour (5:04 p.m.), traffic was extremely light that day because the third game of the World Series between the Oakland Athletics and the San Francisco Giants was about to begin and many commuters were already at home in front of their television sets.

The collapse of the Nimitz Freeway was extensively analyzed by numerous organizations.[1-4] Their main goal was to assist in the design of new freeway structures or to retrofit existing freeway structures so that they would be more resistant to collapse from future earthquakes. However, the failure of the Nimitz Freeway also provides a dramatic and wonderful physics lesson. A previous article on the Northridge earthquake complements this one, allowing the reader to note the similarities and differences between the two earthquakes.[5] Many readers will find strong parallels between this freeway collapse and the Tacoma Narrows Bridge collapse.[6] Similar to the bridge collapse, there is even an excellent video on the Nimitz Freeway collapse that makes a wonderful pedagogical addition to this article.[3]

Fig. 1. A section of the collapsed Cypress Street Viaduct of the Nimitz Freeway (permission to reproduce, Lloyd Cluff, cover page in Ref. 4).

The Loma Prieta earthquake measured 7.1 on the Richter scale. It was the strongest earthquake in the San Francisco Bay Area since the San Francisco earthquake of 1906. Both the earthquake of 1906 and 1989 were caused by the San Andreas fault line, which runs roughly along the coast of California. By 1989 numerous accelerometers had been installed around the Bay Area, including one in Emeryville, within one mile of the collapsed Nimitz Freeway. The ground acceleration at the Emeryville site, shown in Fig. 2, lasted about 15 seconds, was primarily in the lateral direction (the

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maximum vertical acceleration was less than 0.1*g*), roughly oscillatory with a period of about 1.0 second, and had a maximum east-west acceleration of 0.26*g* (near the earthquake's epicenter, accelerations greater than 0.6*g* were measured).[3] Even though Emeryville is about 81 km from the earthquake epicenter, the acceleration was amplified because the land originally had been part of the San Francisco Bay, but was filled with soil that had not been compacted. The Nimitz Freeway only collapsed in areas where it was built on noncompacted bay fill.[7] In contrast, accelerometers on solid rock in San Francisco and closer to the earthquake epicenter experienced accelerations less that 0.1*g*. A very simple and elegant explanation of the dramatically increased acceleration on liquefied soil is found in Ref. 5. If you double integrate Fig. 2, you get the lateral velocity and position of the land surface as a function of time; the maximum oscillatory displacement was about 8.0 cm.

A sketch of one-half of the double-deck freeway support structure (called a "bent" by civil engineers) is shown in Fig. 3, along with the most common failure mode. The freeway failed at the hinge between the top of the lower deck and the bottom of the upper deck. Civil engineers considered two possible explanations for this failure—a static mechanism and a dynamic mechanism. (From a physics point of view, these are poor choices of names. Nonresonant and resonant mechanisms would have been preferable, but I will use the original names.) The static mechanism asserts that the hinge failed because it could not exert a large enough force to accelerate the upper deck when the lower deck was accelerating up to 0.26*g*. When this structure was built in 1959, the state code for bents called for a design to withstand a lateral acceleration of 0.06*g*. The various hinges that were installed in the Nimitz Freeway were designed to withstand lateral accelerations between 0.10 and 0.21*g*. Since the Loma Prieta earthquake generated accelerations that exceeded these design specifications, the hinges would fail and the upper decks would fall onto the lower decks. However, more recent computer calculations suggest that the hinges could have provided the needed force to accelerate the upper decks to 0.3*g*, greater than the maximum acceleration of the lower deck.[7]

The dynamic mechanism asserts that the lower deck's oscillatory motion due to the ground motion

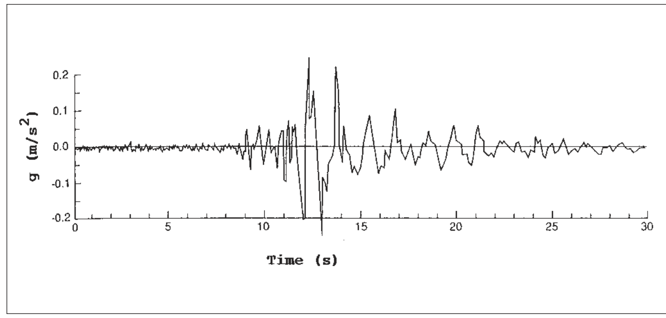

Fig. 2. Plot of ground east-west acceleration as a function of time recorded at Emeryville during the Loma Prieta earthquake.[4] The vertical axis is acceleration in units of *g* (9.8 m/s^2).

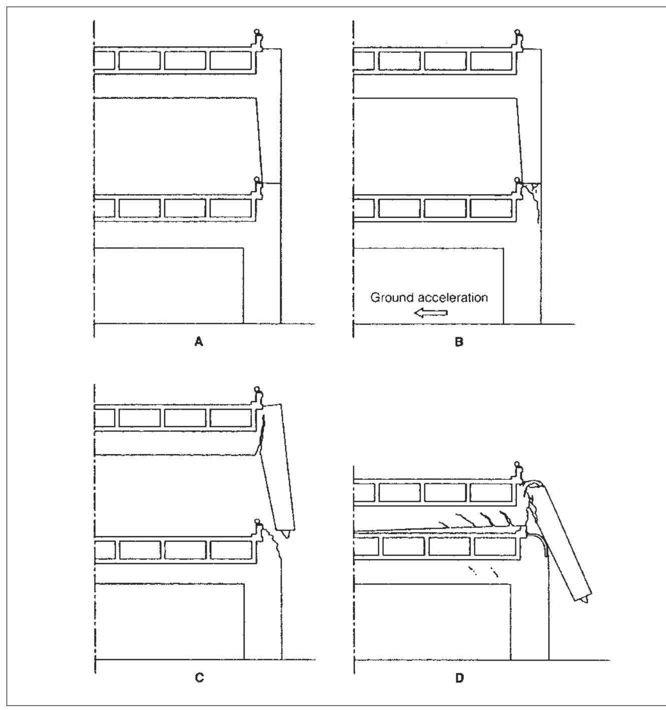

Fig. 3. Typical failure time sequence from A to D of half of a support structure (bent) during the Loma Prieta earthquake.[2]

excited a transverse (east-west) natural mode of the upper deck—a resonance between the frequency of the lower deck's motion and a natural mode of the upper deck—that generated a large enough motion of the upper deck to destroy the hinges.[8] Experiments after the Loma Prieta earthquake on standing portions of the Nimitz Freeway observed a transverse (east-west) mode at 2.6 Hz; a frequency (Fourier) analysis of Fig. 2 established that there was a significant component of the east-west acceleration at 2.6 Hz.

Finally, computer calculations demonstrated that the acceleration of Fig. 2 would generate a large enough amplitude in this transverse mode to cause the hinges to fail.[7]

The above discussion is a simplification. First, there is some evidence that there was a domino effect, where the collapse of one upper deck induced the neighboring upper deck to collapse.[4] When the standing part of the viaduct was destroyed after the earthquake by damaging one pillar, this domino effect was observed. Second, it should be emphasized that these computer calculations are approximate and their conclusions open to uncertainty.

Finally, the reader might be curious about the fate of this stretch of the Nimitz Freeway after the earthquake.[9] The whole double-deck section was replaced with a ground-level freeway. A similarly constructed Embarcadero Viaduct built on bay-fill in San Francisco, which was damaged but did not collapse during the Loma Prieta earthquake, was demolished and not replaced. Other freeway viaducts in the Bay Area were quickly retrofitted; for example, steel shells were erected around concrete columns, and high-strength rods were drilled through and under existing column footings.[9] Finally, state codes for freeway bridges and viaducts were dramatically upgraded, and new freeway viaducts and bridges are now constructed to be less rigid, more deformable in a destructive, energy-absorbing (nonelastic) way, but able to survive such deformations without collapsing.

In conclusion, the failure of the Nimitz Freeway during the Loma Prieta earthquake can provide a dramatic introduction to a number of important physics concepts—Newton's second law and forced harmonic oscillation. Combining this material with the available video creates a fascinating and educational case study for any high school, college, or university physics class.

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