Comparison of Base Shears Estimated from Floor Accelerations and Column Shears

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This paper compares base shears computed from floor accelerations (inertial base shear) and column shears (structural base shear) for two mid-rise, multi-story buildings due to a suite of 30 earthquake ground motions. The presented results demonstrate that the inertial base shear exceeds the structural base shear in the median by 10% to 20% and may exceed the structural base shear by as much as 70% for individual ground motions. Therefore, it is concluded that the inertial base shear computed from strong motion records should be used with caution to estimate the structural base shear. [DOI: 10.1193/1.3610247]

INTRODUCTION

Buildings are typically instrumented with accelerometers at a selected number of floors: low-rise buildings (one to three stories) at every floor; and mid- and high-rise buildings at base, roof, and a few intermediate floors. The accelerations at instrumented floors are interpolated (e.g., Naeim, 1997, Naeim et al. 2004, Goel 2005, Limongelli 2003) to estimate accelerations at remaining floors, which are then used to estimate base shear by adding all floor inertial forces above the base (Figure 1a); the inertial force at a floor is computed as the product of floor acceleration and floor mass (e.g., Jennings 1997, Naeim 1997). The base shear computed using the aforementioned procedure is referred to as the "inertial base shear" in the rest of this paper and is denoted by V_{bxI} in the longitudinal direction and V_{byI} in the transverse direction. It is useful to emphasize that this procedure is an approximate method to obtain an estimate (not necessarily an exact value) of the base shear demand during an earthquake without the need for detailed structural analysis.

The inertial base shear demand is often compared with the base shear capacity, estimated from either pushover analysis (e.g., Goel 2005) or the code design base shear (e.g., Naeim 2004). The base shear capacity from pushover analysis or the code base shear is indicative of the sum of shear forces in all columns at the building's base (Figure 1b). The base shear defined by the aforementioned procedure is referred to as the "structural base shear" in rest of this paper and is denoted by V_{bxR} in the longitudinal direction and V_{byR} in the transverse direction.

A large number of buildings are instrumented in seismically active regions such as California. The strong motion records obtained from such buildings during earthquake ground shaking are increasingly being used for making decisions about the need for detailed post-earthquake inspection of such buildings. One of the criteria triggering detailed inspection

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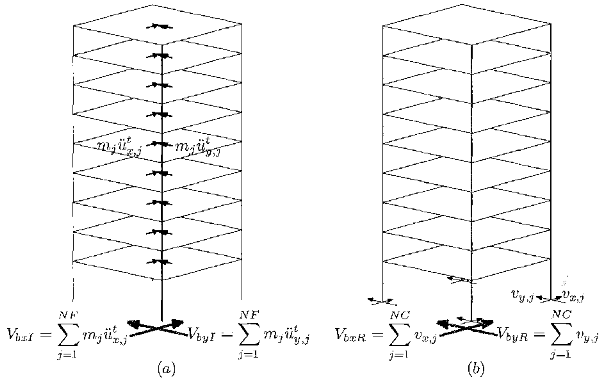

Figure 1. Computation of base shear: (a) Inertial base shear computed from summation of inertial floor forces and (b) structural base shear computed from summation of column shears.

involves comparing inertial base shear induced in the building during an earthquake ground shaking with its structural base shear capacity (or code design base shear): if the inertial base shear exceeds the base shear capacity, the building is expected to have suffered damage requiring detailed inspection.

Observations from buildings that were strongly shaken during the 1994 Northridge earthquake indicate that inertial base shear may not always be a good indicator of damage in the building. For example, consider the performance of two buildings—the 20-story reinforced-concrete hotel in North Hollywood and the 19-story steel office building in Los Angeles for which the inertial base shear demand exceeded the base shear capacity (or code design base shear) during the 1994 Northridge earthquake (Naeim 1998, Goel 2009). However, post-earthquake inspection (Naeim 1997, 1998) indicated insignificant damage in the North Hollywood building (minor cracking in beam and columns) and minor damage in the Los Angeles building (bucking in a few braces in upper stories). Clearly, these buildings were not deformed much beyond their linear elastic limits. This indicates that the inertial base shear should not have exceeded the structural base shear if the inertial base shear was a good approximation of the structural base shear.

The apparent discrepancy noted above between peak inertial and structural base shears can be attributed to the following three factors. First, the error may occur in estimation of peak inertial base shear because interpolation procedure used to estimate accelerations at non-instrumented floors may lead to inaccurate floor accelerations which in turn will lead to inaccurate floor inertial forces and inertial base shear. Second, the error may occur in estimation of peak structural base shear capacity from pushover analysis due to errors associated with modeling and analytical assumptions. Third, discrepancy between inertial and structural base shears occurs due to contribution of damping forces.

A comprehensive study to fully understand the contribution of each of the three factors requires that error corresponding to each factor be examined individually. This is possible only if the building is instrumented to measure accelerations at each floor and shears in all columns at its base. Clearly, such a study requires detailed laboratory experiments on well instrumented multistory buildings. Since experimental study is beyond the scope of this investigation, we rely on results from numerical simulations. For this purpose, responses (floor accelerations, column shears) of two buildings—the 20-story reinforced-concrete hotel in North Hollywood and the 19-story steel office building in Los Angeles—are computed from nonlinear response history analysis (RHA) for a suite of 30 ground motions recorded during past earthquakes using the structural analysis software *Perform3D* (CSI 2006). The *Perform3D* computer models used FEMA-356 (ASCE 2000) recommendations for beam/column force-deformation behavior. Further details of these buildings, modeling techniques, and ground motions are available in Goel (2009, 2010) and Goel and Nishimoto (2009). The inertial and structural base shears are then computed from the nonlinear RHA results and compared to demonstrate the difference between the two for multistory buildings.

It is useful to note that the approach used in this investigation eliminates the errors associated with interpolation of accelerations because accelerations are available at all floors. Furthermore, it also eliminates the errors associated with modeling and analytical assumptions because both inertial base shear and structural base shear are for the same model, albeit a computer model.

Recently, Bernal and Nasseri (2009) and Bernal (2010) investigated error in the base shear due to different interpolation procedures and presented Kalman Filter and Minimum Norm Response Corrector methods for minimizing this error. The base shear considered in these investigations was the inertial base shear because it was assumed that the inertial base shear is generally a good approximation of the structural base shear (Bernal 2010). Therefore, the error investigated in Bernal and Nasseri (2009) and Bernal (2010) is due to interpolation procedures, which differs from the error between inertial and structural base shears being investigated in this paper.

COMPARISON OF INERTIAL AND STRUCTURAL BASE SHEARS

Compared in this section are the inertial and structural base shears in the two selected buildings due to the selected ground motions. It is useful to note that the ground motions in this investigation were not selected to match a particular design spectrum but to ensure that they will induce different levels of inelastic behavior in the selected buildings. It was found during analysis that the selected buildings experienced excessive deformation due to several of the ground motions and collapsed. Results for these ground motions have been excluded from those presented in this section.

Examined first were the time-variations of inertial and structural base shears for selected ground motions. This examination showed that the inertial base shear matched the structural

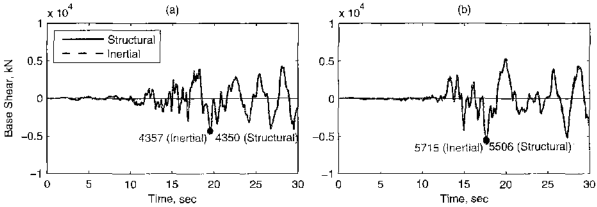

Figure 2. Comparison of inertial and structural base shears in the North Hollywood hotel for Earthquake No. 14: (a) Longitudinal direction and (b) transverse direction.

base shear quite well for some earthquakes but the difference was very large for others. Since the length limitation of this paper prohibits presentation of all results, selected results are presented for each of the two buildings in Figures 2 to 5 to demonstrate cases where the two base shears matched quite well and where they differed significantly; results for other ground motions are available in Goel (2009).

The results for the North Hollywood hotel indicate that the inertial base shear tracks the structural base shear quite well for earthquake No. 14. Furthermore, the peak value of inertial base shear is essentially equal to the structural base shear in the longitudinal direction (Figure 2a) and exceeds the structural base shear by no more than 4% in the transverse direction (Figure 2b). While the inertial base shear tracks the structural base shear quite well for earthquake No. 9, the peak value may differ by about 10% in the longitudinal direction (Figure 3a) and by about 20% in the transverse direction (Figure 3b).

The results presented for the Los Angeles building indicates a very good match between inertial and structural base shears for earthquake No. 4 (Figure 4). For earthquake No. 15,

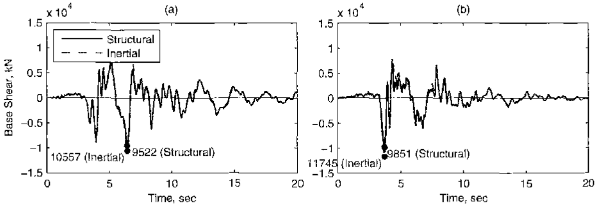

Figure 3. Comparison of inertial and structural base shears in the North Hollywood hotel for Earthquake No. 9: (a) Longitudinal direction and (b) transverse direction.

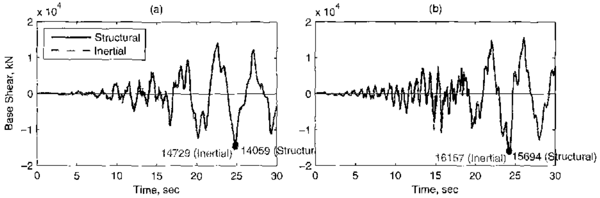

Figure 4. Comparison of inertial and structural base shears in the Los Angeles building for Earthquake No. 4: (a) Longitudinal direction and (b) transverse direction.

however, the inertial base shear differs significantly from the structural base shear not only in the peak value but in the frequency content as well (Figure 5). The peak value of inertial base shear exceeds the structural base shear by about 70% in the longitudinal direction (Figure 5a) and by about 35% in the transverse direction (Figure 5b). The results of Figure 5 also show that the inertial base shear has significant high-frequency content compared to the structural base shear. Therefore, it appears that the inertial base shear may significantly exceed the structural base shear for ground motions with significant high-frequency content.

Examined next are the ratios, V_{bxI}/V_{bxR} and V_{byI}/V_{byR}, of the inertial and structural base shears for the two buildings. The results are presented in Figures 6 and 7 for earthquakes for which the building did not to collapse. The presented results include ratios for individual earthquakes along with the median values.

The results presented in Figure 6 for the North Hollywood hotel show that the ratio V_{bI}/V_{bR} for some earthquakes can be as high as 1.2. This indicates that inertial base shear may exceed the structural base shear by up to 20%. The median value of the ratio is,

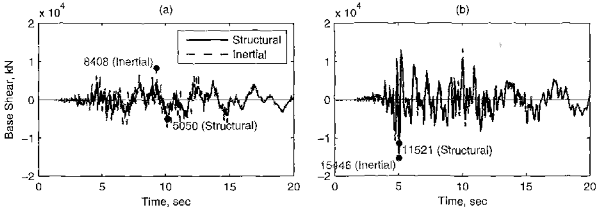

Figure 5. Comparison of inertial and structural base shears in the Los Angeles building for Earthquake No. 15: (a) Longitudinal direction and (b) transverse direction.

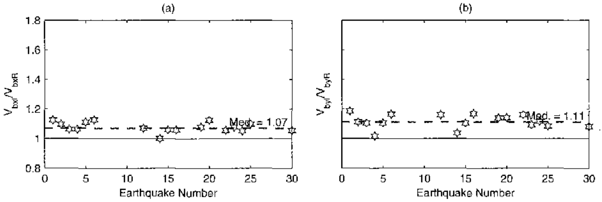

Figure 6. Ratio of peak inertial and structural base shears for North Hollywood hotel: (a) Longitudinal direction and (b) transverse direction.

however, much smaller: the median ratio is from 1.07 (Figure 6a) to 1.11 (Figure 6b). Therefore, it may be expected that the inertial force will exceed the structural base shear in the median by about 5% to 10%.

The results presented in Figure 7 for the Los Angeles building show that the median value of the ratio varies from 1.07 (Figure 7a) to 1.22 (Figure 7b) implying that the inertial base shear exceeds the structural base shear in the median by 5% to 20%. For an individual earthquake, the ratio can be as high as 1.7 in the longitudinal direction (Figure 7a) and 1.4 in the transverse direction (Figure 7b).

The discussion so far indicates that the median inertial base shear exceeds the structural base shear by 10% to 20%. For an individual earthquake, however, the inertial base shear may exceed the structural base shear by as much as 70%. Furthermore, the large discrepancy between inertial and structural base shears occurs for ground motions with significant high-frequency content. Therefore, inertial base shear should be used with caution as an estimate of the structural base shear in buildings with motions recorded during earthquake ground shaking.

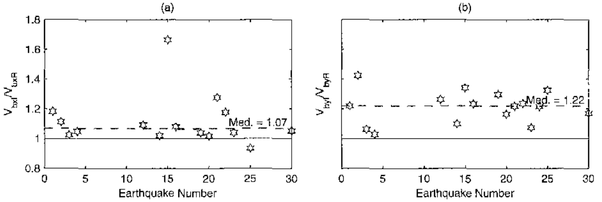

Figure 7. Ratio of peak inertial and structural base shears for Los Angeles building: (a) Longitudinal direction and (b) transverse direction.

Recently, Bernal (2010) also examined the ratio of inertial and structural base shears for three buildings: a 6-story commercial building in Burbank, a 10-story residential building in San Jose, and a 13-story commercial building in Sherman Oaks. The results presented for these three buildings in Bernal (2010) also confirm the above-noted findings in this paper.

CONCLUSIONS

This investigation examined if the inertial base shear, defined as a summation of floor inertial forces above the building's base with the floor inertial forces computed by multiplying the floor masses with the total floor accelerations, can provide an accurate estimate of the structural base shear which is equal to the sum of shears in all columns at the building's base. It was demonstrated that the median inertial base shear exceeds the structural base shear by 10 to 20%. For individual earthquake ground motions, however, the inertial base shear may exceed the structural base shear by as much as 70%. It was also demonstrated that the large discrepancy between inertial and structural base shears occurs for ground motions with significant high-frequency content. Therefore, inertial base shear should be used with caution as an estimate of the structural base shear for individual ground motion.

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