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SPATIAL DISTRIBUTION OF RESPONSE OF MULTI-STORY STRUCTURES FOR SIMULATED GROUND MOTIONS

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SUMMARY

Computer simulation of earthquakes in an idealized geophysical region with strike-slip and thrust fault mechanisms produces synthetic ground motions at more than 25,000 grid points. These ground motions are used to investigate the structural response of moment-resisting steel building frames (3-story and 9-story) using nonlinear structural models (material and geometry) at each grid point. The analysis shows that the location and orientation of a building affects the amount of roof drift as well as the vertical distribution of story drift. Building frames located in the forward directivity region and oriented in the fault-normal direction have significant story and roof drifts. The 9-story buildings in forward directivity zone show large story drifts in top and bottom floors. Therefore, current seismic design procedures may not prevent formation of soft stories under near-fault ground motions in the forward-directivity zone. The regional simulations provide insight into the distribution of building damage that may be produced by large earthquakes.

INTRODUCTION

Densely populated urban regions are vulnerable to large earthquakes because of the potential for widespread damage to engineered structures. Most studies to date have examined the performance of individual structures or types of structures based on recorded ground motions, particularly from recent earthquakes in Northridge, California [1], Kobe, Japan, [2], Taiwan [2] and Turkey [2]. Studies such as by Alavi [3] have shown that near-fault ground motions can be particularly damaging to buildings. Although the libraries of ground motion records are becoming richer as recording station coverage is denser in near-fault regions, the sporadic occurrence of large earthquakes in heavily instrumented regions make it difficult to investigate the spatial distribution of structural performance and provide a complete picture of the distribution of damage that can occur in a region. To address this issue, seismologists are increasingly utilizing large-scale computer simulations to compute synthetic ground motions based on

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source parameters and models of the geological structure [4]. Hall et al. [5] simulated a thrust fault to examine the effect of near-fault ground motions on long-period buildings, including 20-story steel frame buildings and base isolated buildings. The simulations showed that buildings near the fault have very large deformation demands, which are not adequately represented in current seismic design procedures.

In a recent study, Bielak et al. [6] performed earthquake simulations for different types of rupture mechanisms and studied the synthetic ground motions. Such earthquake simulations using realistic finite element models of geophysical structure can provide ground motions with higher spatial resolutions than possible with field recordings of earthquakes. Using a spatially dense set of ground motions obtained from this type of earthquake simulation, the performance of structures can be studied on a regional basis. Fenves et al. [7] studied the response of single degree-of-freedom (SDOF) models of structures in a region for a hypothetical strike-slip fault and thrust fault. SDOF systems are often used to idealize the earthquake response of multi-degree-of-freedom (MDOF) models of buildings [8, 9], so the spatial distribution of SDOF response provides insight into the performance of a wide range of buildings. Although an SDOF model can indicate the amount of overall displacement, SDOF models generally provide a poor representation of local deformation quantities such as story drift and plastic rotation in structural members.

The objective of this paper, therefore, is to examine the distribution of deformation in MDOF models of a building over a region subjected to a large near-field earthquake. Of particular interest is the inelastic response of moment-resisting frame buildings. This study examines how the location and orientation of a building affects the amount of deformation and the vertical distribution of deformation in moment-resisting frames.

SIMULATED GROUND MOTION IN AN IDEALIZED REGION

The ground motion simulations have been performed as a part of a research program on seismic performance of urban regions (SPUR) [6]. The domain is 20 km by 20 km in area and 10 km deep. It has two layers of rock: the 1 km top layer has shear wave velocity of V_s=2000 m/sec while the half-space bellow it has V_s=3460 m/sec. Absorbing boundaries are used in addition to a buffer zone. The finite element model is able to resolve frequencies up to 2 Hz for this velocity structure. Simulations have been performed for two scenarios, a strike-slip fault and thrust fault, with moment magnitudes of 6.0 and 5.8, respectively [6]. The spatial distributions of peak horizontal ground velocity and displacement over the region are presented in Figures 1 and 2, respectively. The contours of peak ground motion are based on uniform 120x120 m grid spacing. In the strike-slip fault case, the fault-normal and fault-parallel directions are defined using the surface projection of the fault. Thus, for the strike-slip fault scenario, the fault-normal direction refers to global Y direction and the fault-parallel direction is the global X direction. For the thrust fault, the fault-normal direction is defined as normal to the up-dip extension of the buried fault plane to where it intersects the ground surface. Thus, the fault-normal direction in the thrust fault case is the global X direction. Conversely, the fault-parallel direction is the global Y direction.

Propagation of the rupture toward a site with a velocity that is almost as large as the shear wave velocity causes most of the seismic energy to arrive as a large single-pulse motion. The radiation pattern of the shear dislocation on the fault causes this large pulse motion to be oriented perpendicular to the fault. These forward directivity effects are observed in zones where the rupture front propagates toward a site and the direction of the slip on the fault is aligned with the site [10]. As shown in the Figures 1 and 2, the forward directivity effect is concentrated in a zone along the fault in the rupture direction for strike-slip fault scenario. For the thrust fault scenario, the forward directivity zone is concentrated at sites in the up-dip direction. In the forward directivity zone, the fault-normal component of the velocity is a large single pulse, whereas the fault-parallel component of ground motion is considerably smaller. The ground velocity attenuates more rapidly than ground displacement, as can be seen by comparing Figures 1 and 2.

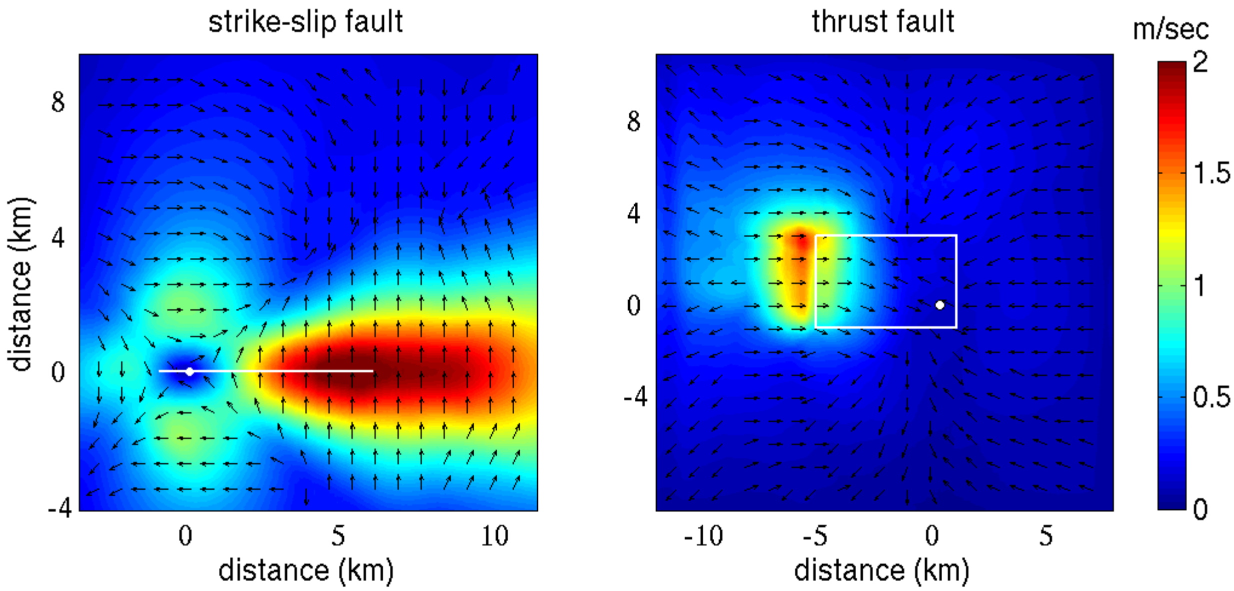

Figure 1. Spatial distribution of peak ground velocity. The arrows show the orientations that the peak magnitudes occur in, the line represents the surface projection of the fault, and the dot represents the epicenter of the earthquake.

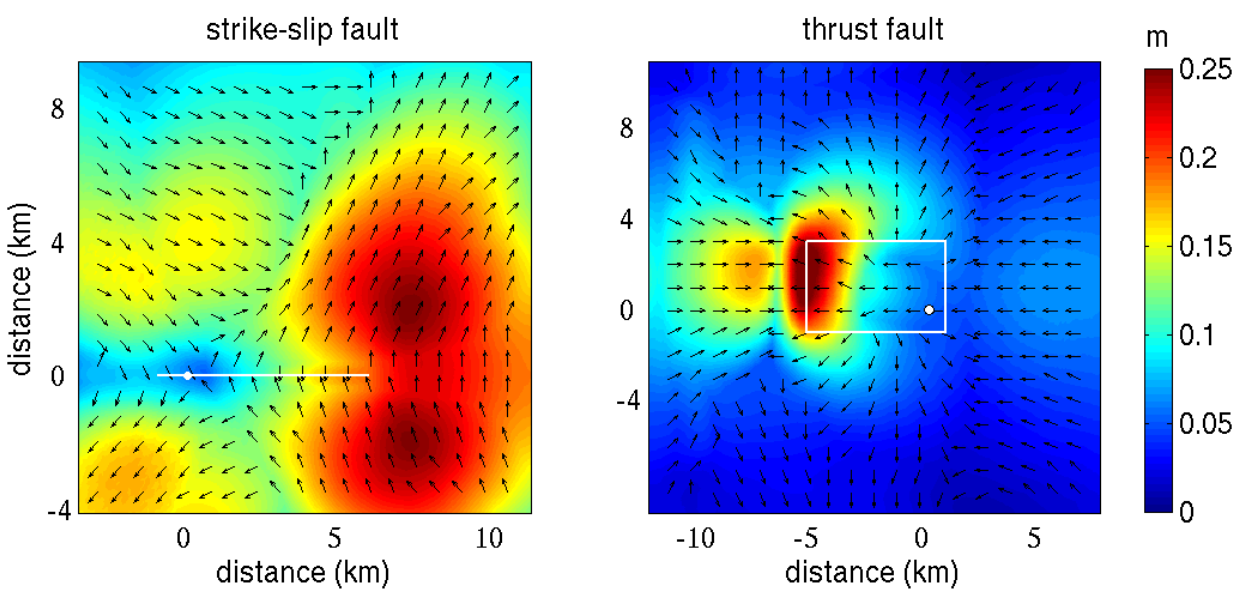

Figure 2. Spatial distribution of peak ground displacement. The arrows show the orientations that the peak magnitudes occur in, the line represents the surface projection of the fault, and the dot represents the epicenter of the earthquake.

STRUCTURAL MODELS AND PARAMETERS

Modeling of Multi-story Frame Buildings

The multi-story buildings analyzed in this study are two steel moment-resisting frame structure (a 3-story and 9-story), designed as part of the SAC steel project [11]. The buildings were designed according to the 1994 *Uniform Building Code* for Los Angeles site conditions. The floor plans and elevations for the two buildings are shown in Figure 3.

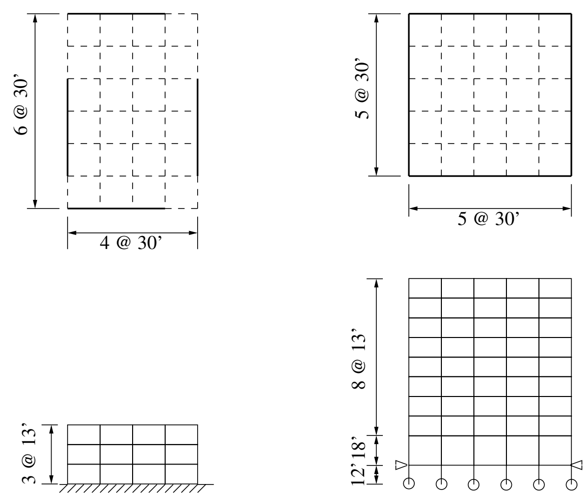

Figure 3. Plan view and elevations of the SAC frames. (solid line: moment-resisting frame, dashed line: gravity frame)

For this study, the buildings are modeled as 2-dimensional frames and analyzed using the OpenSees software [12]. The frames are modeled using centerline dimensions. Nominal values of steel yield stress, 50 ksi for columns and 36 ksi for beams, are used. The structural elements are modeled using OpenSees non-linear beam-column elements, which are based on a force formulation [13] and account for the spread of plasticity along the member. Numerical integration of the element force-deformation relation is done at five cross-sections along the length of the element. Each cross section is discretized using uni-axial fibers. The fibers implement an elastic-plastic-hardening stress-strain material model. Large displacement kinematics is used for the beam-column elements. To consider the P-Δ effects of the gravity frames in the building, a leaning column carrying the weight of the tributary area at each floor is attached to the model of the moment-resisting frame. In the elastic range, the fundamental vibration period of the 3-story frame is 1.0 sec and that of the 9-story frame is 2.3 sec.

Structural Response Parameters

The response of a SDOF structure to an earthquake ground motion can be described using the non-dimensional displacement ductility demand and the base shear coefficient. The spatial distribution of these SDOF response parameters is quite variable within the region of study, because it depends on the period of the structure and the spatial distribution of the ground motion. Furthermore, the orientation of SDOF systems has a significant effect on the structural response because of the large differences between fault-normal and fault-parallel ground motions in the near-fault zone [7].

SDOF response, however, cannot represent the distribution of deformation along the height of a multi-story building. Furthermore, there is a particular concern about multi-story building response to a near-fault ground motion [9,5]. The essential structural response parameters for MDOF models of moment-resisting frame buildings subjected to earthquake ground motions are roof displacement, story drift, and local deformation of structural elements, such as plastic hinge rotation. The roof displacement is presented as the maximum roof drift ratio, which is the absolute maximum roof displacement divided by the height of the building. The story drift ratio, a ratio of story displacement and story height, is presented as the envelope of maximum story drifts at each story. The plastic rotation of a beam element is computed using the moment-curvature response history of the two element cross sections near its end. These engineering demand parameters can be correlated to structural performance and damage, and are therefore important for developing design provisions and regional loss estimation.

Buildings designed for a strength specified using current design code provisions are expected to have a fairly uniform distribution of story drift over the height of the building. The vertical distribution of the story drift, however, is strongly influenced by the ground motion characteristics [14]. The simulated ground motions for the strike-slip and thrust fault near-field earthquake scenarios are used to investigate the spatial variability of vertical distribution of story drift in moment-resisting frames.

SPATIAL DISTRIBUTION OF STRUCTURAL RESPONSE

This section examines the spatial distribution of deformation of the 3-story and 9-story building models in the region for the two scenario earthquakes. The response is computed at each grid point in the region for a total of 25,281 locations. Two separate computations are done at each location for building frames oriented in the fault-normal and fault-parallel directions. The spatial distributions of roof drift and maximum story drift are examined, along with the vertical distribution of story drift in buildings at selected sites in the region.

Strike-slip fault scenario

Maximum roof drift
Figure 4 shows the spatial distribution of maximum roof drift ratio for the 3-story and 9-story building frames in fault-normal and fault-parallel directions. The spatial distribution of roof drift varies significantly across the region and depends on the location and orientation with respect to the fault. For fault-normal motions, large roof drift occurs in the forward directivity zone. Significant roof drifts also occur in the fault-parallel direction near the epicenter, as expected from the distribution of ground velocity shown in Figure 1.

The maximum roof drift of 3–story buildings is 4.6% (21.5 in) in fault-normal direction. It occurs in a structure located near the end of the fault in the forward directivity zone. The spatial distribution pattern for roof drift of 3-story buildings is similar to that of the peak ground velocity as shown in Figure 1. In the forward directivity zone, the ratio of fault-normal to fault-parallel roof drift is approximately four. However, at a few sites along the fault projection line this ratio is as large as ten.

The maximum roof drift of 9-story buildings is 2.1% (30.7 in) in fault-normal direction. It occurs in a structure located near the end of the fault in the forward directivity zone. In the forward directivity zone, the ratio of fault-normal to fault-parallel roof drift is approximately three in the region within 2 km around the fault, while outside this region the magnitudes of fault-normal to fault-parallel response are approximately equal.

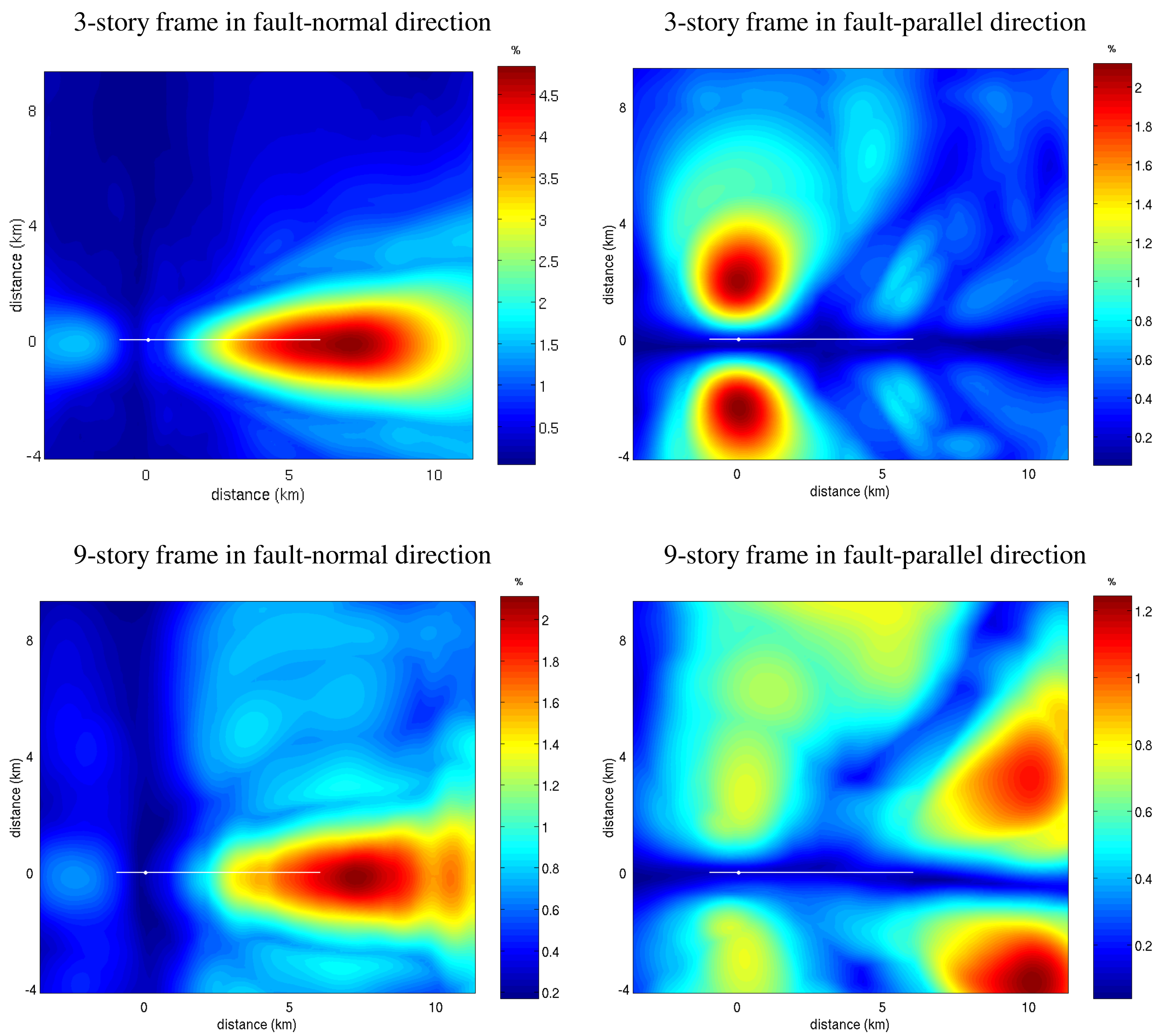

Figure 4. Spatial distribution of maximum roof drift ratio for strike-slip fault scenario.

Maximum story drift
Figure 5 shows the spatial distribution of maximum story drift of the 3-story and 9-story buildings in the fault-normal and fault-parallel directions. As with the roof drift, the distribution of maximum story drift has a large amount of spatial variability and it depends on the orientation of the building.

For the fault-normal direction, the locations of buildings with the largest story drift are concentrated in the forward directivity zone. A significant number of buildings in that zone develop story drifts larger than 3%. The maximum story drift among all 3-story buildings is 6.1% (9.5 in). For the fault-parallel direction, the 3-story buildings in a region close to the epicenter have the largest story drift. For 9-story buildings, the largest story drift is 3.7%. It occurs in the fault-normal direction in buildings located along the surface projection of the fault between the epicenter and the end of the fault. For the fault-normal direction, the larger story drifts are concentrated in the forward directivity zone along the fault. For the fault-parallel direction, the location of maximum story drift is offset north and south of the epicenter.

For structural design and analysis procedures, it is desirable to understand the relationship between the maximum story drift and the roof drift of MDOF structures. Comparison of the spatial distribution of maximum roof drift and maximum story drift provide insight into this relationship. For the 3-story buildings in both fault-normal and fault-parallel directions, the spatial distribution of maximum story drift is similar to that of maximum roof drift. The ratio of maximum story drift to roof drift varies between 1.1 and 2.2. There is a systematic spatial variability of the relationship between maximum story drift and roof drift for 3-story buildings. For the 3-story buildings in the fault-normal direction, the ratio of maximum story drift to roof drift is typically 1.5 in forward directivity zone. At distance greater than 2 km from the fault, the maximum story drift is 1.2 or less of the roof drift, indicating slightly more uniform distribution of deformation over the height than buildings located within 2 km of the fault.

For 9-story buildings, the spatial distribution pattern of maximum story drift in Figure 5 is somewhat different than the maximum roof drift distribution shown in Figure 4. The ratio of maximum story drift to roof drift varies from 1.1 to 4.4 in the fault-normal direction and from 1.1 to 4.8 in the fault-parallel direction. For the fault-normal direction, the maximum story drift is 2.5 times greater than the roof drift near the epicenter, but in the forward directivity zone the maximum story drift is about 2.0 times the roof drift. The large difference between the two responses and the large spatial variation of the differences indicate that the distribution of deformation over the nine stories is not uniform and it varies substantially depending on the location of the building with respect to the fault.

The spatial distribution of plastic rotation of beams in the building has similar distribution with the maximum story drift, although it is not shown because of space limitations, indicating that there is a close relationship between the story drift and the plastic deformation of the beams in the frame.

Vertical distribution of peak story drift

Building response simulation indicates that the vertical distribution of deformation in a building is affected by the location of the building. To provide insight into this issue, Figure 6 shows the vertical story drift distribution at selected sites in the region. For 3-story buildings in fault-normal direction, the story drift at top floor is greater than at other stories at sites within approximately 2 km of the fault. Most of the buildings at sites more than 2 km from the fault remain elastic and the vertical distribution of story drift is fairly uniform. For 3-story buildings in the fault-parallel direction, the story drift at the top floor is largest in the area of large ground velocity.

For the 9-story buildings in fault-normal direction, the vertical distributions of maximum story drift show systematic differences at sites within 2 km from the fault compared with sites located farther away. From the epicenter to the end of the fault, the drift at top floor is greater than at other stories, but the drift at lower stories is also significant. At the sites near the end of the fault in the forward directivity zone, the drift at lower floors is greater than other floors. For fault-parallel direction and the sites near the epicenter, the largest drift occurs in the top stories.

It is interesting to note that the site in the backward directivity zone produces significant story drift in the fault-normal direction for both 3-story and 9-story buildings, with the largest drift occurring in the top story.

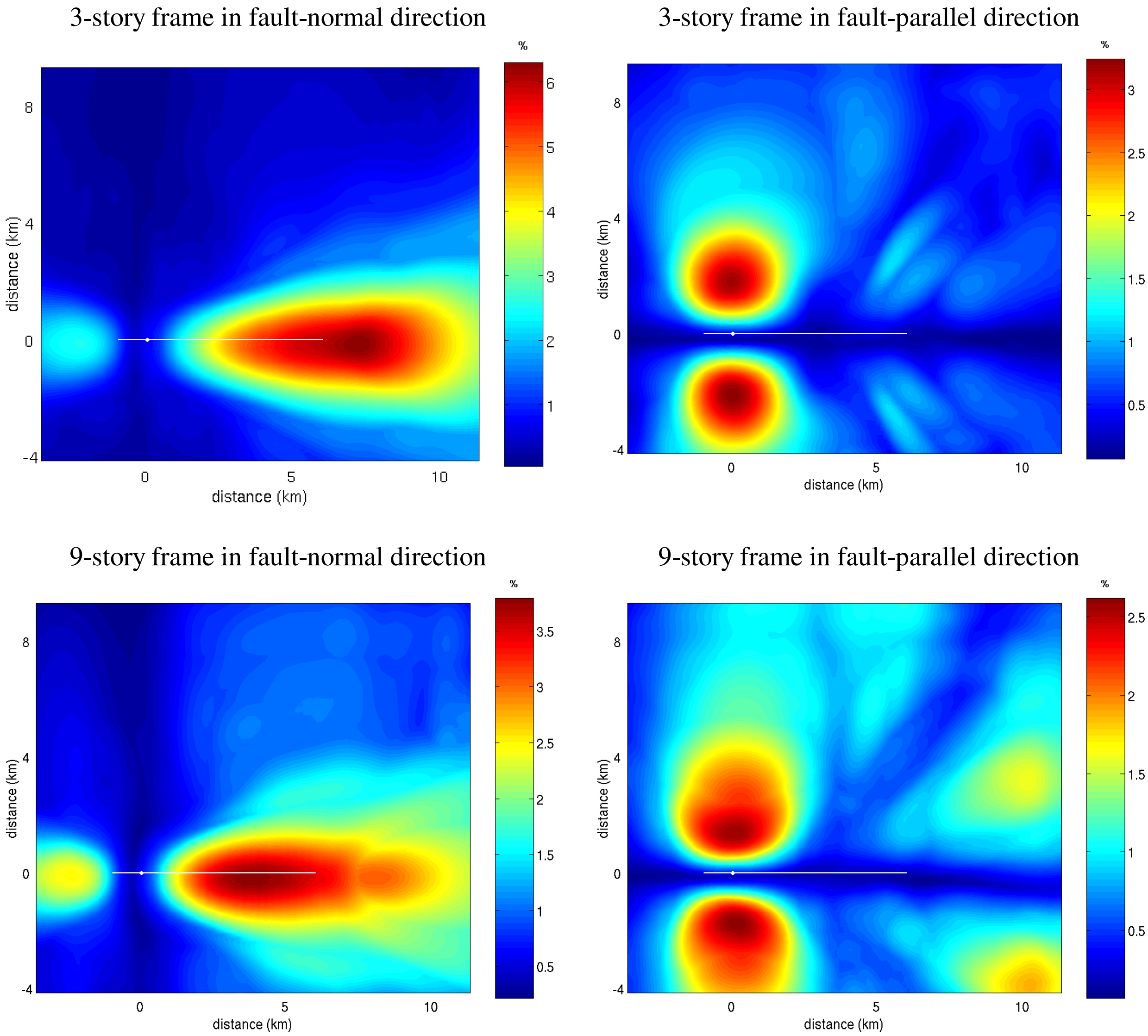

Figure 5. Spatial distribution of maximum story drift for strike-slip fault scenario.

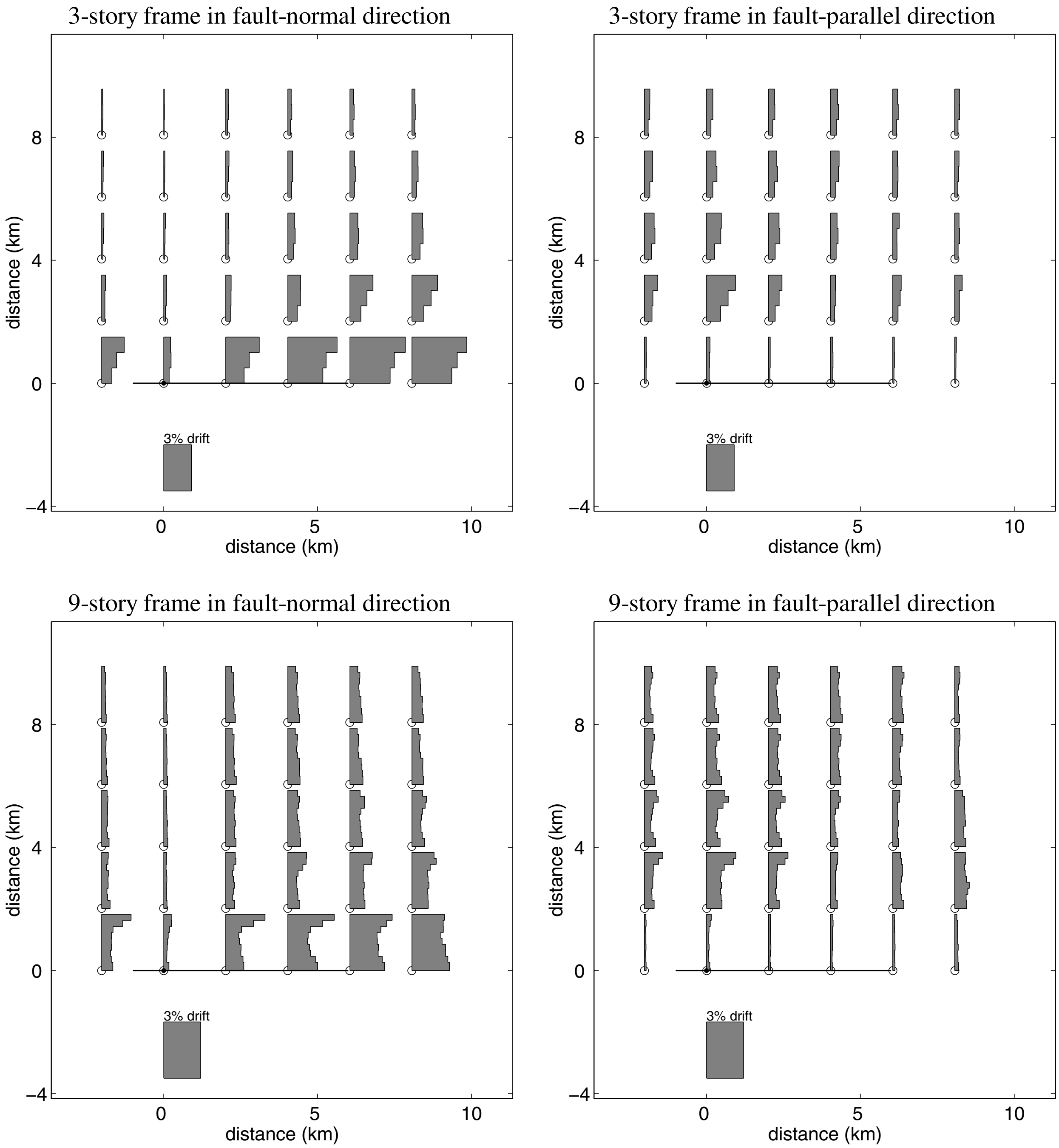

Figure 6. Vertical distribution of maximum story drift at selected sites for strike-slip fault scenario.

Thrust fault scenario

Maximum roof drift

Figure 7 shows the spatial distribution of maximum roof drift ratio for the 3-story and 9-story building frames in fault-normal and parallel directions for the thrust fault scenario. The maximum roof drift varies considerably and depends on the location of the site and orientation of the buildings with respect to the fault. The maximum roof drift of the 3-story buildings is 4.4% (20.6 in) in fault-normal direction near where the fault plane would intersect the ground surface. As with the strike-slip fault scenario, the spatial distribution of the 3-story building response for the thrust fault scenarios is similar to the peak ground velocity in Figure 1. In the fault-parallel direction, the largest magnitude of building displacement is concentrated in locations near the north edge of the projection of the fault. The ratio of fault-normal to fault-parallel roof drift is greater than four in the areas of large ground velocity.

The maximum roof drift of 9-story buildings is 1.5% (22 in) in the fault-normal direction and is located near the up-dip from the hypocenter. In the fault-normal direction, the largest magnitude of roof drift is concentrated in the forward directivity zone. In the fault-parallel direction, the zone of largest roof drift is 2 to 6 km away from the up-dip projection of the fault. The ratio of fault-normal to fault-parallel roof drift is greater than three near up-dip projection of the fault

Maximum story drift

Figure 8 shows the spatial distribution of maximum story drift for the 3-story and 9-story buildings in fault-normal and parallel directions.

The maximum story drift of 3-story buildings is 6.1% (9.5 in) in the fault-normal direction in the region of large response observed for the ground motion and the roof drift. In the fault-normal direction, the greater magnitude of story drift is concentrated in the forward directivity zone. Many of the structures in that zone show significant story drift larger than 3%. The spatial distribution pattern of maximum story drift is similar to that of maximum roof drift in both directions. In the forward directivity zone the ratio of maximum story drift to roof drift is about 1.5 in the fault-normal direction. At locations, the maximum story drift is 1.3 (or less) times the roof drift. For fault-parallel direction, ratio of story drift to roof drift is 1.2 at most of the sites.

The maximum story drift of 9-story buildings is 3.5% in the fault-normal direction and is located near up-dip projection of the fault. For the fault-normal direction, the large story drift of 9-story buildings is concentrated in the forward directivity zone. The spatial distribution of maximum story drift is similar to that of the roof drift in fault-normal direction but is somewhat different in the fault-parallel direction. In the forward directivity zone, the maximum story drift is three or more times greater than the roof drift in fault-normal direction. At some of the locations in the forward directivity zone this ratio is close to seven. Maximum story drift in the fault-normal direction is considerably larger than in the fault-parallel direction.

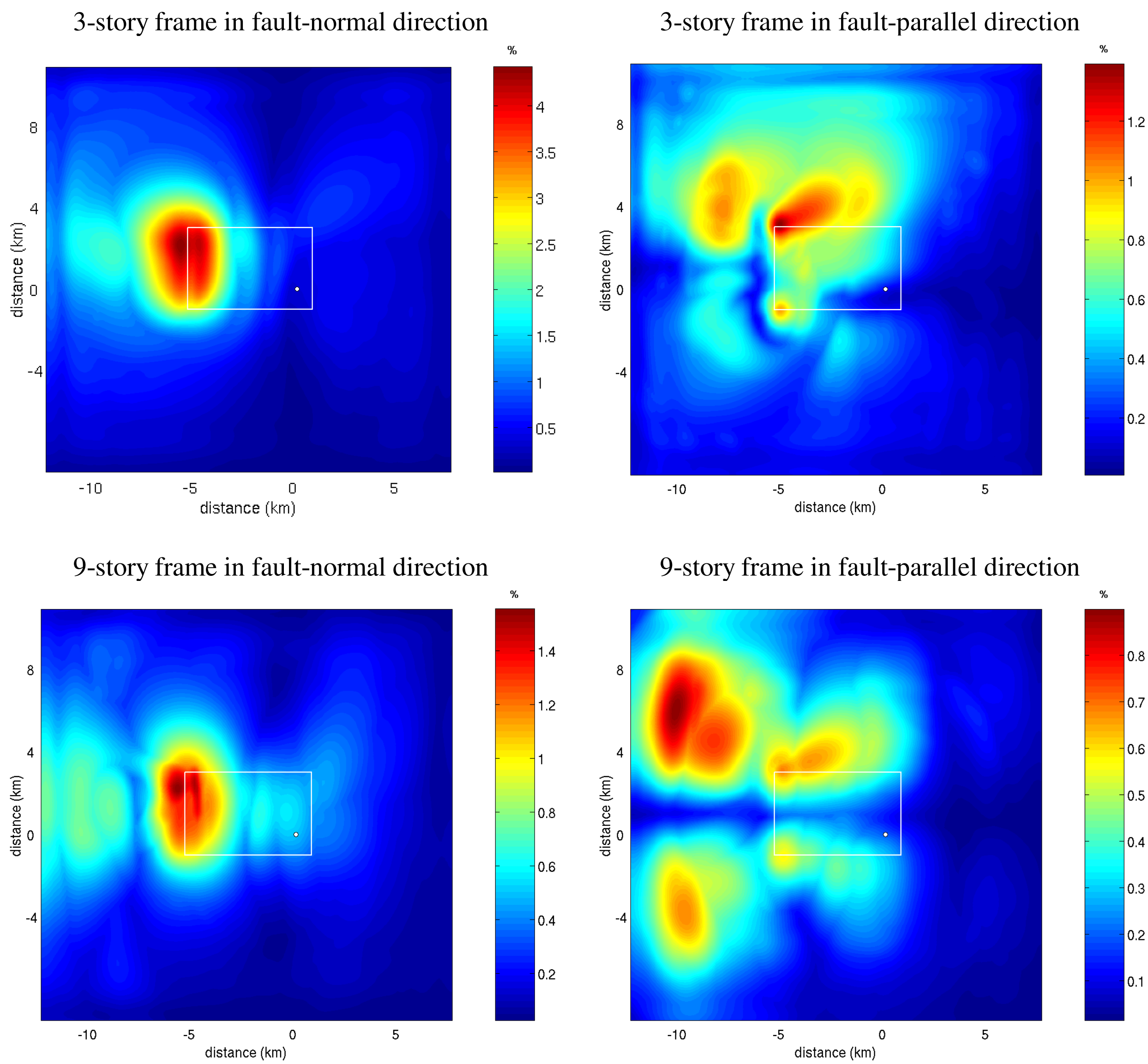

Figure 7. Spatial distribution of maximum roof drift ratio for thrust fault scenario.

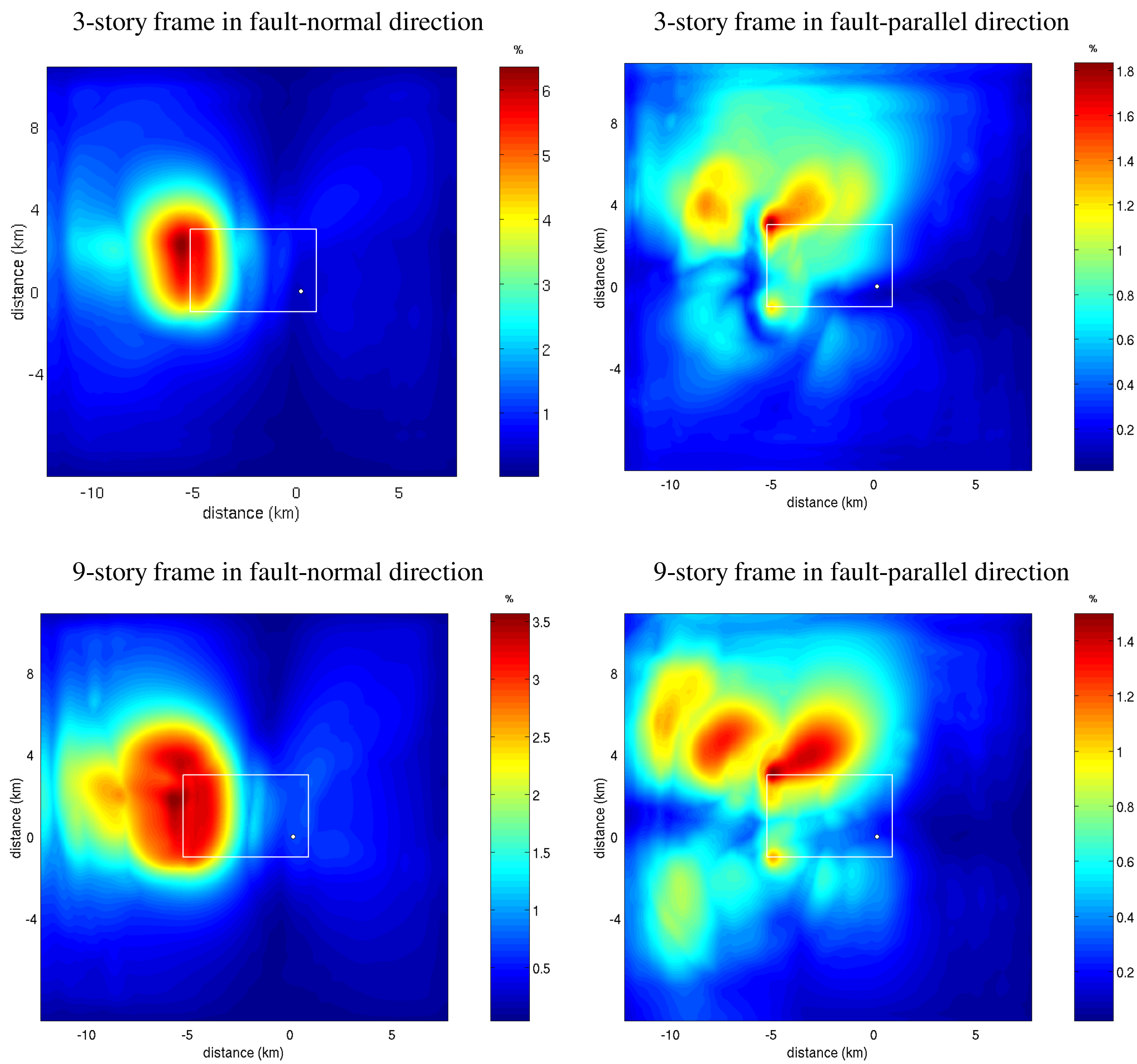

Figure 8. Spatial distribution of the maximum story drift for thrust fault scenario.

Vertical distribution of peak story drift
Figure 9 shows the vertical story drift distribution at selected sites for the thrust-fault scenario. For 3-story buildings in fault-normal direction, the story drift at top floor is greater than at other stories in the forward directivity zone. Most of the buildings elsewhere in the region respond elastically and the vertical distribution of the maximum story drift is fairly uniform. For 3-story buildings in the fault-parallel direction, the story drift distribution is fairly uniform for buildings in the region.

For 9-story buildings in the fault-normal direction, vertical distribution of maximum story drift shows that the higher floors, from 7 to 9, have more than twice the drift of the lower floors for buildings in the forward directivity zone. For fault-parallel response, the story drift is fairly uniform over the height of the building at most locations.

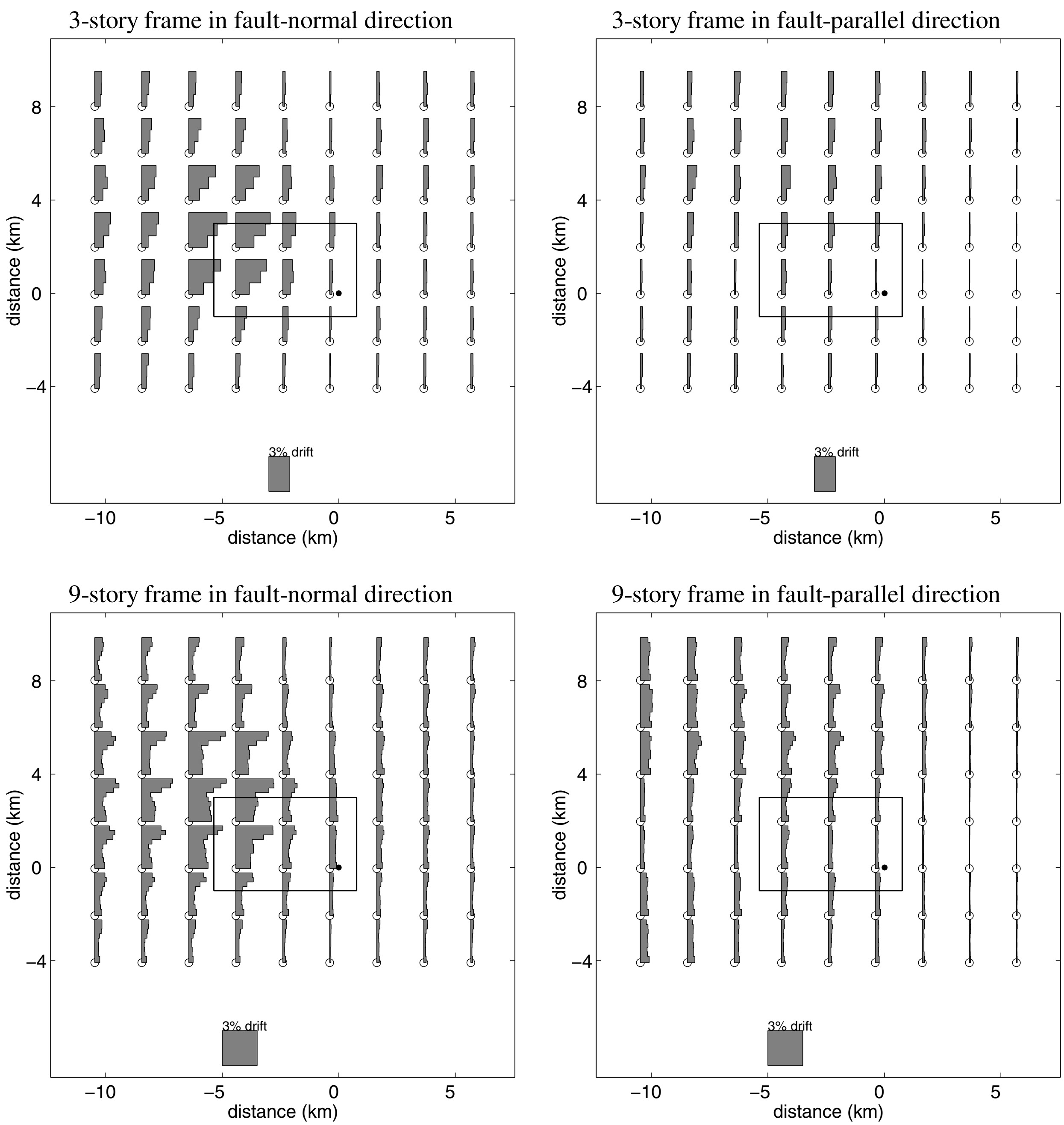

Figure 9. Vertical distribution of maximum story drift at selected sites for thrust fault scenario.

CONCLUSIONS

A regional simulation of ground motion for two idealized fault scenarios was used to examine the distribution of deformation in MDOF models of a building over a region subjected to idealized large near-field earthquake. Of particular interest is the inelastic response of moment-resisting frame buildings measured using roof drift, maximum story drift, and distribution of maximum story drift over the height.

This study examined how the location and orientation of a building affects the amount of deformation and the vertical distribution of deformation in moment-resisting frames.

It was found that large deformations occur in buildings located in the forward directivity zone and oriented in the fault-normal direction for the strike-slip and thrust fault scenarios. The maximum roof drift of 3-story and 9-story buildings shows spatial variability similar to that of peak ground velocity. The relationship between maximum roof drift and maximum story drift is, also, location-dependent. Although the maximum story drift provides important information about how close the building is to its connection rotation limits, vertical distribution of story drift is even more important for assessing the possibility of developing soft stories. The results of simulations show that vertical distribution of the maximum story drift varies with the location of the structure. The 9-story buildings in the forward directivity zone show large story drifts in the top and bottom floors, which indicates that standard design procedures do not prevent soft-story formation for near-fault ground motions in the forward-directivity zone. Such localization of deformation in tall buildings is can be interpreted in terms of wave propagation of the pulse-type ground motion along the structure [5]. Building design procedures are needed to control the amount of inelastic deformation in the soft stories for near-fault ground motions.

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