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Inelastic Dynamic Analysis of a Reinforced Concrete Frame with Deformable Joints

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ABSTRACT

Reinforced concrete beam column joints are critical elements in frame structures under earthquake loading. These elements can experience high shear and bond slip deformations that may contribute significantly to the story drift. Moreover, the joint capacity may be exceeded leading to a joint shear failure. This condition is particularly pronounced in lightly reinforced concrete structures where the beam column joints are typically the weakest link in the lateral load resistant mechanism. A finite element model that considers bond slip and shear deformations in the beam column region has been developed. This model is used in the analysis of a three-story reinforced concrete frame structure with different joint detailing strategies. Pushover analyses as well as time history analyses are conducted on the frame. The response of the structure using different joint details is compared to identify the effect of changing these details on the characteristic behavior of the frame. The global response of the structure is assessed by comparing the base shear- roof deflection relationships, the interstory drifts, the maximum story deflections, and the failure mechanisms. Local responses of the joints, the beams, and the columns are also discussed. It is concluded that the deformability of the joint can play a significant role on the overall behavior of the frame structure.

BACKGROUND

Reinforced concrete frame structures designed prior to 1970's in the areas of low to moderate seismicity are historically designed for gravity loads without any considerations to seismic loads. Many of the construction details used in these buildings do not meet the current code requirements and are contrary to proper seismic detailing practice. The major concern is the lack of proper joint details. Under seismic loading, beam-column joints can experience high shear and bond-slip deformations, which can contribute significantly to the story drift. A new finite element model has been developed for beam-column connections. In this model, the beam-column joint and the plastic hinge regions in the beams and the columns are idealized as panel zones (Figure 1). The joint is modeled using a single 12-node inelastic element while the beams and columns in the plastic hinge zones are modeled using 10-node inelastic elements. The remaining portions of the beams and the columns are modeled using elastic line elements. The model considers the axial and shear deformations, as well as the bond slip deformations in the joint and in the plastic hinge regions in the beams and the columns. Material non-linearities associated with steel and concrete behavior are taken into account. The proposed model is incorporated into a general-purpose computer program PC-ANSR. Detailed description of the proposed model is given by Elmosi et al. 1998 (a) and (b). In this paper, using the proposed model, a three-story reinforced concrete frame structure with different joint detailing strategies is analyzed. This includes a rigid, a well detailed and a poorly detailed joint. The purpose of using a rigid joint is to investigate the effects of ignoring the shear and the bond slip deformations in the critical region on the overall response of the structure.

DESCRIPTION OF THE STRUCTURE

The building configuration selected is a typical office building of a frame structure that can be found in many cities in North America. The building is designed at the State University of New York at Buffalo (Hoffman et al. 1992) for gravity and wind loads; in accordance with code requirements prescribed in ACI 318-89 (1989). Seismic loads are not considered in the design of the building. Figure 2 shows a typical bay of the frame with cross-section details, which are identical for all levels. The beam cross section is 230 mm wide by 450 mm deep with 2#5 bars for top reinforcement and 2#6 bar for bottom reinforcement. The column cross section is 300 mm x 300 mm with 4#6 bars. Fair confinement is provided for the beams and the columns by using #3 bars at 200 mm spacing. Two detailing strategies are used for the joint panels. In the first strategy, no stirrups are provided in the joint panels. The second strategy involves using stirrups of 6 # 4 bars at 50 mm for shear resistance. The amount of stirrups used is based on providing sufficient shear resistance

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for the beam-column joint so as to allow the framing beams and columns to reach their full flexural strength. Figure 3 shows the analytical model used for the frame, which is based on the proposed beam-column joint model described in Figure 1.

PUSHOVER ANALYSIS

Pushover analysis is conducted to identify the lateral strength of the structure and its behavior under static loading conditions. The three-story frame is subjected to an increasing monotonic lateral load simulating the seismic base shear. Three analyses are carried out on the frame using a poorly detailed joint having no shear reinforcement, a well-detailed joint having adequate shear reinforcement, and a rigid joint model. Lateral load is applied to the frame at each floor level based on triangular distribution as described in most building codes.

Figure 4 shows the base shear roof displacement relationships for the three frames considered. The Figure shows that the three frames have equal lateral strength. The frame with poorly detailed joints experiences the highest roof displacements followed by the frame with well-detailed joints until the yielding load is reached. On reaching the yield load, roof displacements are largely affected by the deformations of the columns. This causes the effect of joint deformations on roof displacements to diminish. The fact that the three frames reach almost the same base shear at yield indicates that the joint shear strengths for all the frames are sufficient for the framing members to reach their full yield capacity. The joint shear strength provided by the contribution of concrete alone is sufficient to prevent a joint shear failure that would undermine the stability of the structure.

Figure 5(a) shows the distribution of story displacements along the height of the structure at a lateral load of 118.0 kN, which corresponds, to the roof displacement of 200 mm. The Figure indicates that the frame with poorly detailed joints experience the highest story displacements. The frame with the rigid joints shows the least story deflections. Differences in the story deflections are more pronounced at the higher story levels. Figure 5(b) shows the distribution of the interstory drifts over the height of the structure. All the frames show higher interstory drifts at the base, which decrease gradually towards the top of the structure.

Figures 6(a) and (b) show the joint deformations along the exterior column C1. The joint deformations considered are the rotations resulting from shear and the fixed end rotations resulting from bond slip of beam bars in the joint panel region. The Figures indicate that the shear deformations for the poorly detailed joints are higher than those of the well-detailed joints. On the other hand, poorly detailed joints experience less bond slip deformations. Usually, bond slip deformations are more pronounced in the interior joints as compared to the external ones. However, results of the studied frames reveal higher bond slip deformations for the exterior joints. This is due to the fact that beam reinforcement in the interior connections have not reached high strains to cause apparent fixed end rotations as is the case for the exterior joints.

DYNAMIC ANALYSIS

This section describes the response of the three story frame structures to earthquake excitations. The frames are assumed to be fully fixed at their supports and all the supports are assumed to move in phase during earthquake motion. The masses of the tributary floor areas are assumed to be lumped at the beam-column joints. Damping is represented by a linear combination of the mass and initial stiffness. For the dynamic analysis, the acceleration record of El Centro, California, 1940, S-E component with a peak ground acceleration of 0.32g is considered as input ground motion to excite the structure well into the inelastic range of response.

The envelopes of maximum displacements for the frames are shown in Figure7. The response of the frame indicates that it has experienced inelastic deformations. A maximum roof displacement of approximately 156-mm is exhibited by the frame with poorly detailed joints after 5 seconds of the El Centro ground motion. This displacement is beyond the elastic limit as indicated by the pushover analysis shown in Figure 4. The frame with well-detailed joints and the one with rigid joints have exhibited a maximum roof displacement of approximately 134 and 132 mm respectively. The poor detailing of the joints has thus resulted in an increase of about 16% in the frame roof displacements over the one with well-detailed joints and about 18% over the one with rigid joints. In addition, the frames with deformable joints show less deflection at the lower stories of the structure as compared to the frame with rigid joints. Towards the top of the structure, the deflections of the frames with deformable joints get higher. The reason for this distribution is attributed to the shear and bond slip deformations of the beam-column joints, which are more pronounced at the lower stories as will be discussed.

Figure 8 shows the envelopes of interstory drifts. The maximum interstory drifts for the frames with deformable joints occur at the first story when subjected to El Centro earthquake. The frame with poorly detailed joints has exhibited higher interstory drifts than the one with well-detailed joints. The frame with rigid joints exhibits the maximum interstory drifts at the base of the structure. This level of interstory drift is the highest as compared to the two other frames. This is due to the fact that the frame with rigid joints is subjected to higher base shear forces. Moreover the shift of the maximum interstory drifts to the upper stories in the frames with well detailed and poorly detailed joints have served in reducing the maximum interstory drifts.

Figure 9 shows the envelopes of joint shear deformations for the structures studied. The Figure shows that providing adequate shear reinforcement in the joints has significantly reduced their shear deformations. An increase in joint shear deformations of about 110% is noticed for the frames with poorly detailed joints as compared to the well-detailed joints. The maximum shear deformations decrease gradually towards the top of the structure. It is noticed that shear deformations predicted under earthquake loads are much higher than those resulting from the pushover analysis. This is due to the significant deterioration of the shear rigidities of the joints under cyclic load applications.

Figure 10 shows the envelopes of fixed end rotations resulting from bond slip in the joint panels for the structures studied. The Figures show that the bond slip deformations are more pronounced for the frames with well-detailed joints. The joints with higher bond slip deformations have exhibited lower shear deformations. This is in agreement with the results of pushover analysis.

CONCLUSIONS

This paper includes the analysis of three gravity load designed reinforced concrete frames with different joint detailing strategies. Pushover as well as time history analyses are conducted on these frames. Results of the pushover analyses show that the three frames have equal lateral strength. This result is in agreement with available experimental data. The frame with poorly detailed joints shows higher shear deformations and lower bond slip deformations as compared to the frame with well detailed joints. The results of the pushover analyses also show higher deflections and interstory drifts for the frames with deformable joints as compared to the frame with rigid joints. The time history analyses show more pronounced joint shear deformations, as compared to the pushover analysis, due to the degradation of the joint shear rigidities under reversed cyclic load applications. The effect of joint deformations in the frames with deformable joints is to increase their lateral deflections as compared to the frame with rigid joints. The frame with poorly detailed joints shows the highest deflections. Due to high joint shear deformations in the frame with poorly detailed joints, there are lower demands on the beams and thus lower bond slip deformations are experienced in these joints. The frame with rigid joints is able to attract more loads due to their higher stiffness as compared to the other frames.

Finally, it must be noticed that the results presented in this paper are drawn from the limited analyses on a specific frame with a specific earthquake. A more comprehensive study is needed to establish general conclusions on the characteristic behavior of gravity load designed structures.

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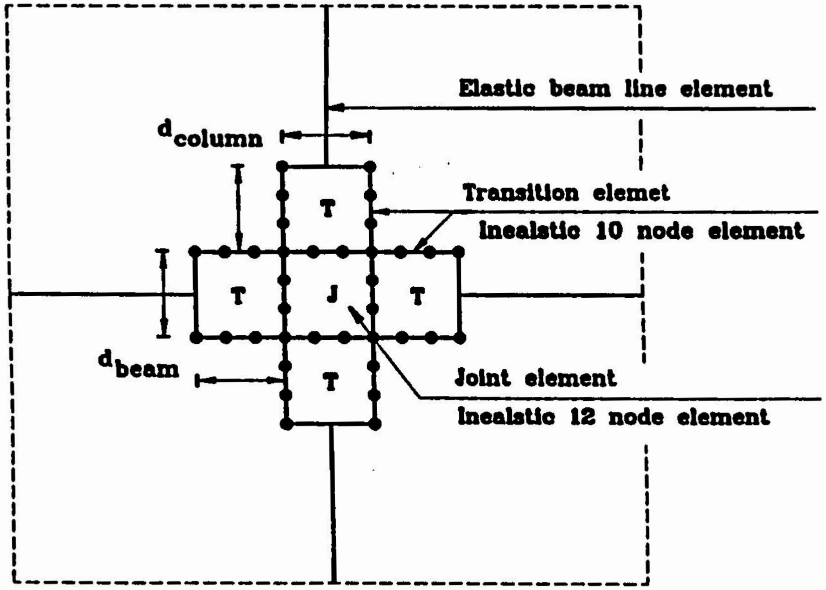


Figure 1 Proposed beam column connection element

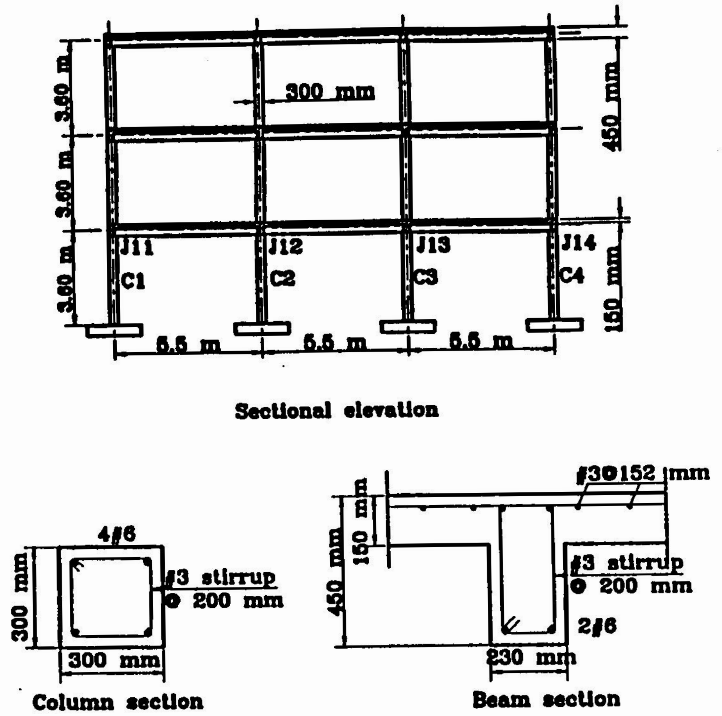


Figure 2 Building elevation and cross-sectional details

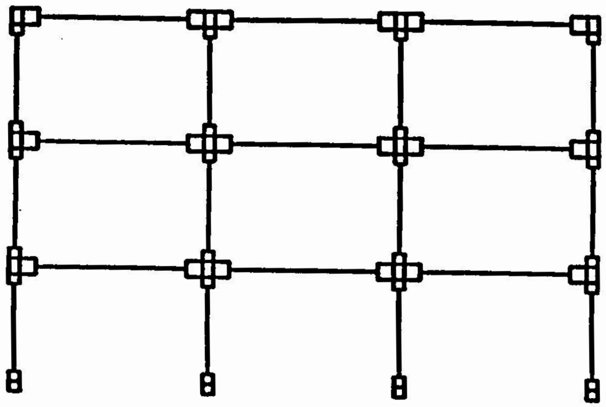


Figure 3 Analytical model

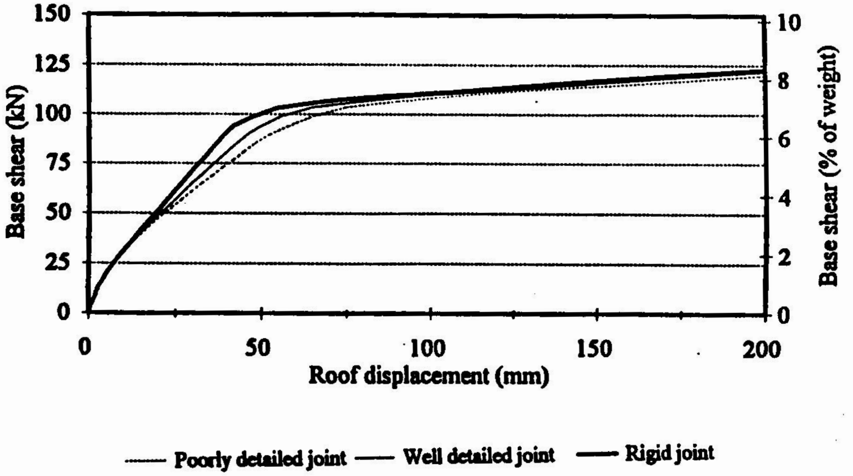
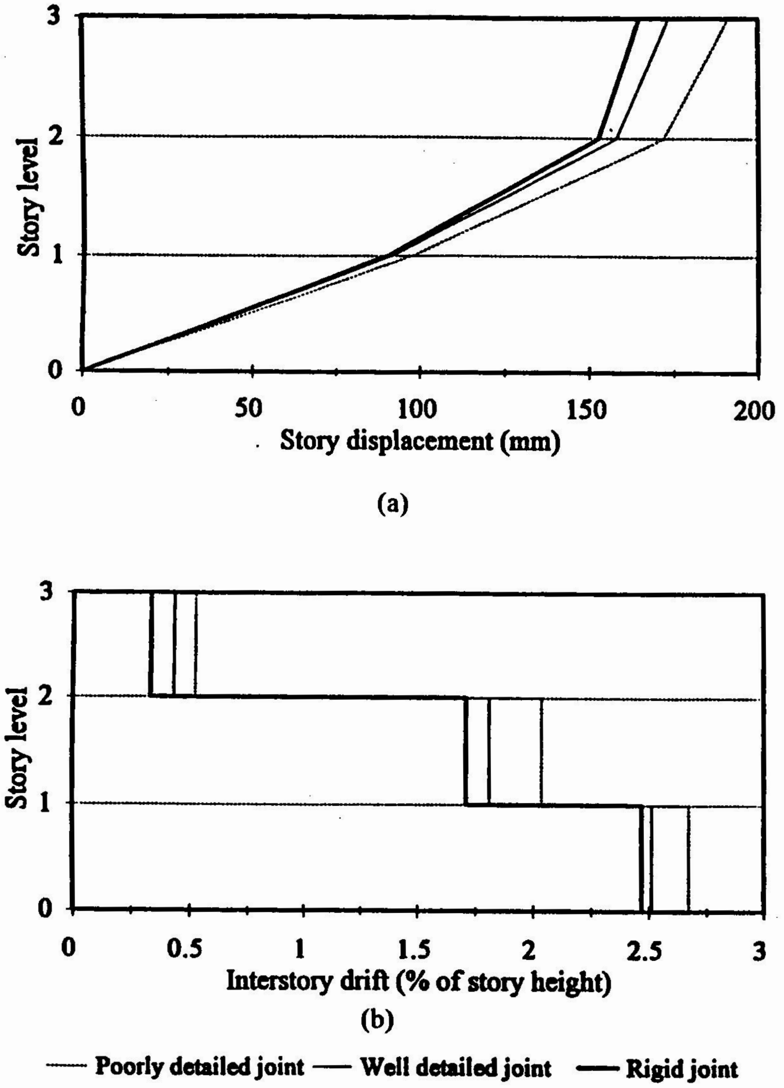


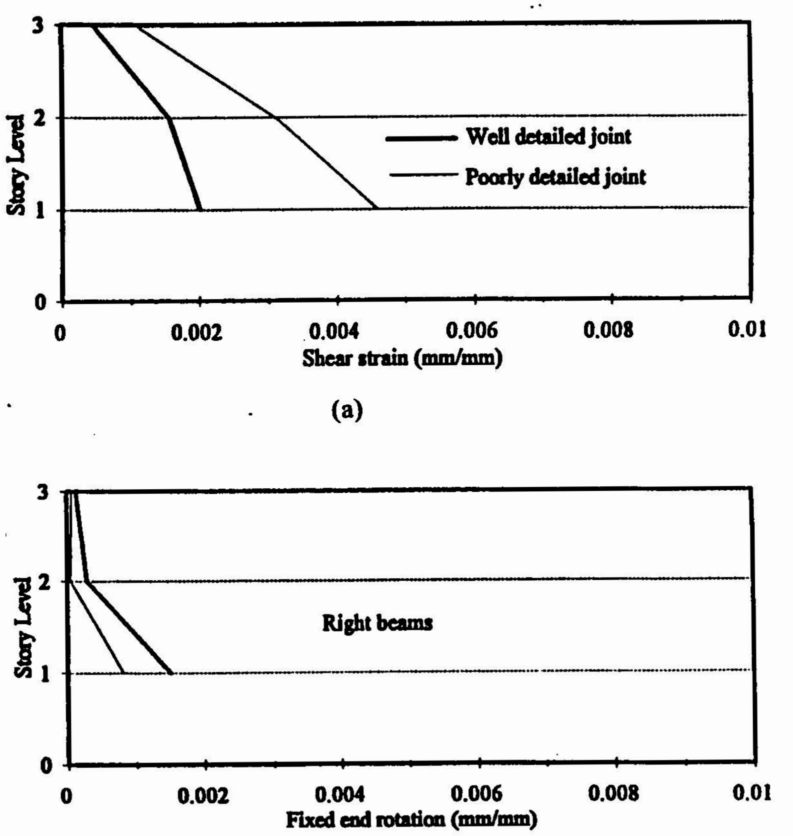
Figure 4 Base shear roof displacement relationship due to pushover loading



(a)

(b)

Figure 5 Maximum story displacements and interstory drifts due to pushover loading



(a)

(b)

Figure 6 Envelopes of joint deforamtions for connections on column C1 due to push over loading

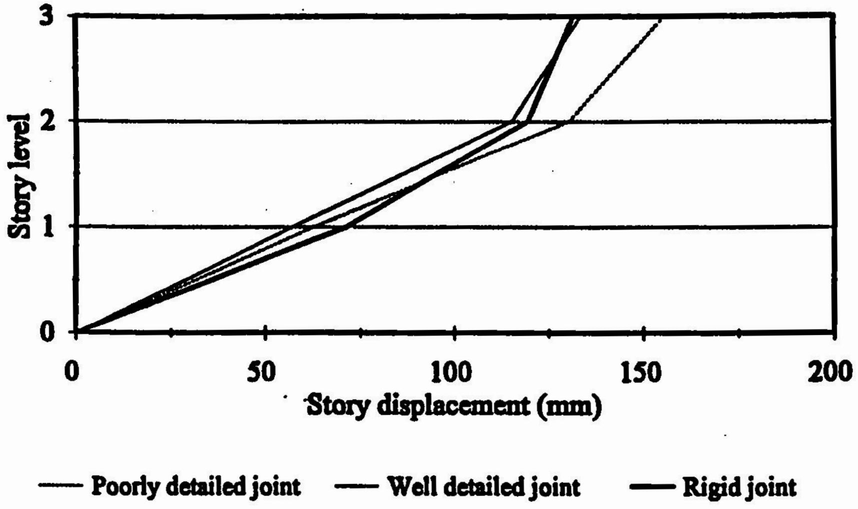


Figure 7 Maximum story displacements due to El Centro earthquake

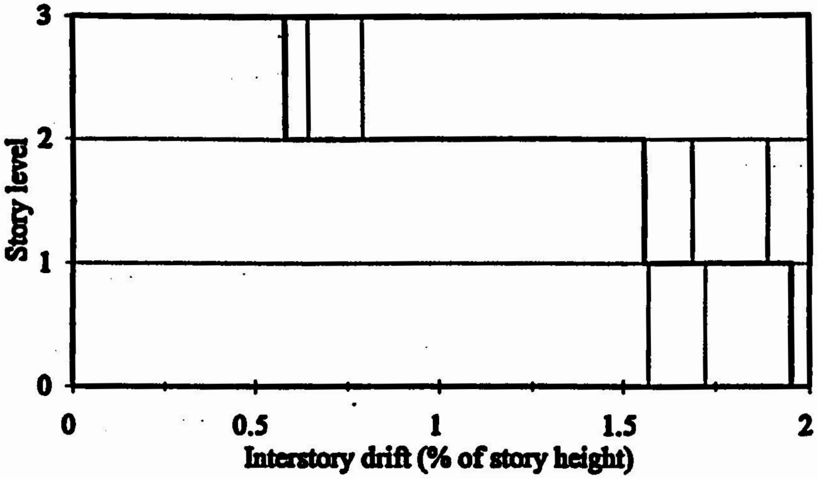


Figure 8 Maximum interstroy drifts due to El Centro earthquake

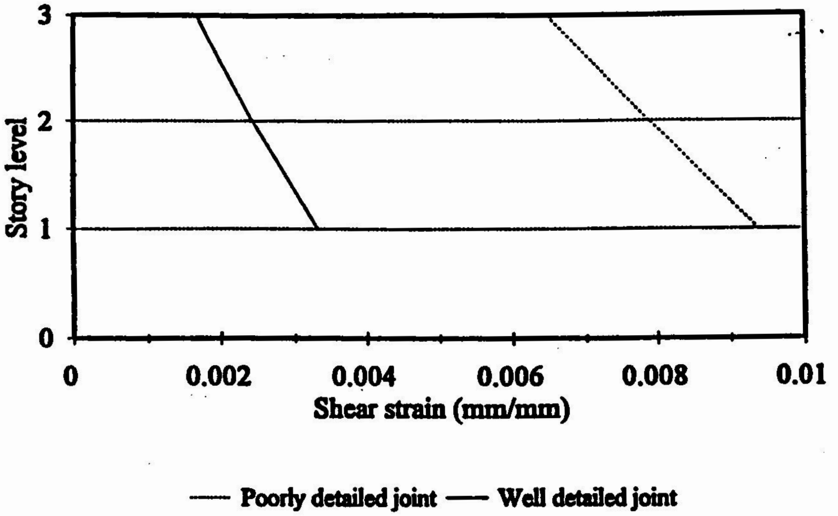


Figure 9 Maximum joints shear deforamtions due to El Centro earthquake

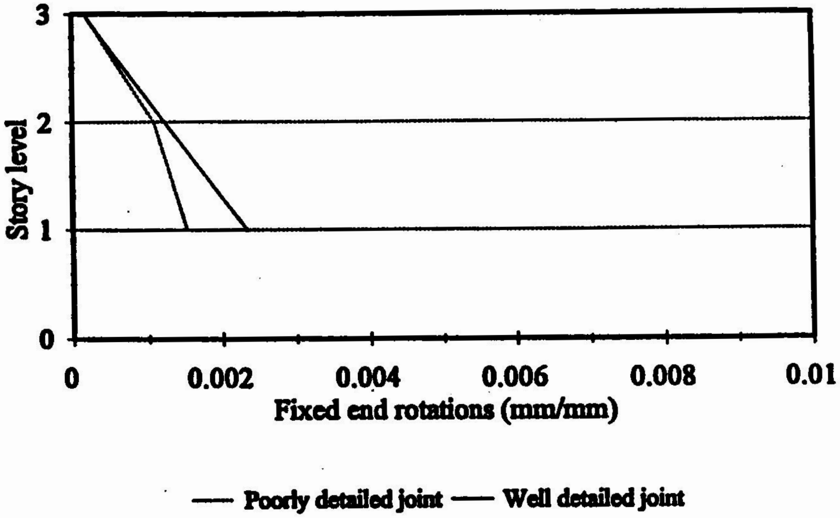


Figure 10 Maximum joints bond slip deforamtions due to El Centro earthquake