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Local ductility of steel elements under near-field earthquake loading

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ABSTRACT

The paper tackles the influence of the near-field earthquakes on the available deformational capacity of steel elements through a global view, joining the results of the wave propagation theory with the one of the local plastic mechanisms. Different from the case of far-field earthquakes, where the structural behavior is dominated by cyclic loading, for near-field earthquakes the structural response is characterized by pulse loading produced by the seismic wave propagation along the height of the structure. Due to this fact, the structure response is dominated by the effect of the strain rate, thus reducing the local ductility and increasing the danger of fracture. After a presentation of the propagation theory applied to near-field earthquakes, the effect of the strain rate on the rotation capacity and on the fractural rotation of the beam elements, considering the fabrication type (rolled or welded) and temperature (room and low) conditions, is studied. It was revealed that the controlled flange buckling, as well as, the yielding ratio is the decisive parameters in order to avoid brittle failures. Finally, a novel representation about the damage produced during the Northridge and Kobe earthquakes due to seismic wave propagation is provided.

1. Introduction

Severe earthquake events, especially during the last two decades, have unveiled that there is an increasing number of cities where the epicenter is situated under very densely constructed areas (e.g. 1994 Northridge, 1995 Kobe, 1999 Izmit, 1999 Chi-Chi, 2010 Port-of-Prince, 2011 Van). The scientific community was obliged to recognize that the characteristics of the ground motions near the source are very different from those at a greater distance from the epicenter. It was revealed that the structures were designed mainly based on the far-field records, without taking into account the actual characteristics of the ground motions. Therefore, the importance of knowing the main characteristics of the near-field earthquakes and their influence on the response of structures is becoming crucial in the seismic design. Nowadays, the practical design under near source actions still remains an open issue. The way to tackle this topic is to relate engineering seismology with the earthquake design of structures.

Conversely to far-field earthquakes, where the ground motions are mainly produced by the surface waves R and L, the near-field earthquakes are directly influenced by the body waves P and S; the surface one producing only secondary effects [1]. As a matter of fact, all the characteristics are different. The main difference is focused on the transmission of the seismic forces to the structure. For far-field earthquakes the transmission of the waves is made by inducing vibration in structure, due to horizontal seismic actions, while for the case of near-field earthquakes the seismic wave propagation is made by the vertical seismic actions.

Generally, the near-field earthquakes are characterized by: very high velocity pulse loading reduced number of pulses, short duration, and important vertical components. Due to the reduced number of pulses and the short duration, the amount of the dissipated energy is reduced. Hence, the problem of ductility must be re-evaluated.

In the case of a structure situated over the source, due to the last ball effect (Newton's cradle), the seismic action is dominated by direct P and S seismic waves which are propagated with very high velocity along the structure. Because of this action with a long pulse, the effect of the strain rate is of paramount importance as it causes brittle fractures on members and connections. For this reason, besides the fulfilling of the ductility requirements, the strength capacity is, also, of equal importance in order to avoid sudden failures.

The existing research works and the current codified rules are mainly concentrated on the structural response requirements [2–8]. Generally, the solution provided against near-field earthquakes was the increasing of the seismic design forces. For instance, the Uniform Building Code '97 [9] and the Chine code GB50011-2001 [10] are among the ones that briefly consider the characteristics of the near-field earthquakes. The majority of the work has been done with respect to the ductility demand, and not to the ductility capacity; very few scientific papers have analyzed the local behavior of the steel members. This is true, due to the fact that the capacity of the testing machine, which examines the effect of the strain-rate on the steel properties, is not capable to capture the strain-rate level which is of interest in the field of the near-source actions. In [11–14] there are some theoretical investigations in the structural response of the steel

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members subjected to loading which produce an important strain-rate. Experimental tests on welded connections, in conditions of dynamic tests, with strain-rate in the field of 10^{-2} sec^{-1} and 5×10^{-2} sec^{-1} are performed in [15]. Indeed, this domain corresponds to the far-field and also to the low and moderate near-field earthquakes. Even though these values, which are reduced in comparison with the ones, produced during a real strong near-field earthquake, they cause a diminution of the cumulative plastic rotation and dissipated energy of about 20%. The authors of [16] underline the possible effects and difficulties to investigate the real domain of action.

From the experimental work performed in [15], due to high strain-rate the yield ratio is increased, about 0.75–0.95, thus impeding the development of the beam plastic rotation at the potential plastic hinge zone and further replacing the ductile plastic collapse into a brittle local fracture.

Starting from this important experimental remark, also demonstrated from real earthquake events (Northridge, 1994, Kobe, 1995, Chi-Chi, 1999), it is obvious that the way to study it is to consider the twofold aspect given by:

(i) The prediction of the decreasing effect on the available ductility due to strain-rate;
(ii) The prediction of the fracture rotation influenced by strain-rate.

Firstly, the available ductility should be evaluated under monotonic loads using the theory of the local plastic mechanism, and accordingly to correct the determined values by considering the specific characteristics of the earthquake type:

$$\text{seismic ductility} = \{\text{correction factor}\} \times \text{monotonic ductility}.$$

The calculation of the monotonic available ductility is presented in [16–18]. Concerning the correction factor, which is generally estimated on the same local plastic mechanism, in this case it is estimated by using the modified mechanical steel properties due to the appearance of strain-rate.

Moreover, a simple approximate methodology is proposed to determine the fracture rotation based on reaching the ultimate strength in a point of plastic mechanism. For both types of local ductility (plastic and fracture) the performances of the DUCTROT-M computer program [18,19] were used. Beyond the conventional way, the analysis of the local ductility is mainly approached under the concept of the near-surface wave propagation in a structure and after that is focused on the main influence of velocity which is strictly related to the first one.

2. New approach for the near-field earthquakes: the wave propagation for P and S body waves

2.1. Ground motion selection in case of near-field seismic action

Generally, the current design is based on the free field records, however in the case of structures analyzed under the action of P and S body waves further the influence of the presence of structures should be investigated.

During an earthquake the rupture of a fault initiates P and S seismic waves, with the tendency to assume a vertical direction towards the Earth surface, as far as the surface layers are concerned (Fig. 1). Then, P-wave motions are thought to be dominant on the vertical direction, while the S-wave motions on the horizontal one. P-waves are always characterized by: higher frequencies, more rapidly attenuation with the horizontal distance, as compared with S-waves. Consequently, the near-field ground motions are described by important vertical components and high frequency energy.

The wave propagation phenomenon gives rise to an important aspect, which is not relevant for far-field recorded ground motions. When the surface is free (Fig. 1a), the recorded ground motions represent only a part of the site movement, because when the waves reach the surface they are reflected back into the Earth, or at the Earth's

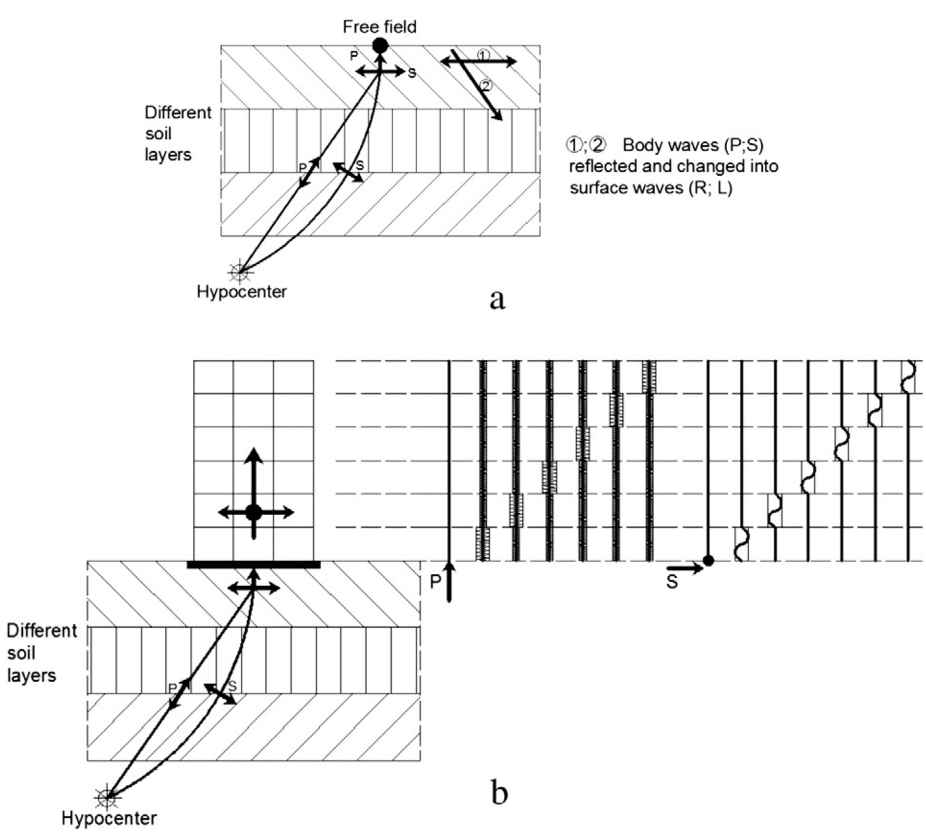

Fig. 1. Ground motion types: (a) free site; (b) site with structure.