Trends and needs for the prediction of the inelastic capacity of steel members considering the differences in seismic loading conditions

Anthimos S. Anastasiadis
Dr. Structural Engineer
GeoStatic Partnership (www.GeoStatic.eu)
Thessaloniki, Greece
e-mail: anstasiadis@geostatic.eu

Tzanetis I. Voghiatzis
Structural Engineer, MSc, PhD candidate
GeoStatic Partnership
Thessaloniki, Greece
e-mail : voghiatzis@geostatic.eu

Constantine I. Sachpazis
Dr. Civil & Geotechnical Engineer
GeoStatic Partnership
Athens, Greece
e-mail: sachpazis@geostatic.eu

1. SUMMARY

The inelastic behaviour of structures strongly depends on the type of earthquake excitation. Moreover the ductility, both the local and global one, as well as the associated strength is depending on the loading history and the rate of loading. The engineering community, starting from the San Fernando earthquake, USA 1971, the Michoacan seismic event, Mexico City, 1985, and further to the Northridge, 1994, USA, and Kobe, 1995, Japan, earthquakes, well recognized and classified the differences between the far source and near source seismic excitations. This paper, through a review of existing literature, is focused upon the effect of both the different loading history and the loading rate on the capacity of steel members. It attempts to provide information in order to reconsider the way of approaching the prediction of the inelastic capacity of steel members.

2. INTRODUCTION

It well recognized that the inelastic behaviour of structures mainly depends on three main parameters, namely, the type of earthquake excitation, the local foundation soil conditions as well as the structural conformation. Moreover the ductility, both the local and global one, as well as the associated strength is depending on the loading history, the rate of loading and the structural detailing.

The engineering community, starting from the San Fernando earthquake, USA 1971, the Michoacan seismic event, Mexico City, 1985, and further the Northridge, 1994, USA, and Kobe, 1995, Japan, earthquakes, well recognized and classified the differences between the far source and near source seismic excitations. After a review of research papers in the field of geotechnical and structural engineering [1], [2], it was demonstrated that the far source earthquakes were related to a cyclic action and low rate of loading, whilst in case of near source earthquakes the load rating is high, developing brittle failures to the base material. Furthermore, the vertical action is another important factor contributing to failures by fracture. However, due to the inherent uncertainties related to the seismic actions the considerations presented herein would be considered as a general tendency of the inelastic behaviour of steel elements.

As it was revealed from past earthquake events, beyond the hazard described by the seismic excitation and the geotechnical conditions, the vulnerability of a structural system, as derived by inefficient materials, construction defects, inferior execution, is another factor contributing to the potential damage. Research projects, like the SAC, [3], RECOS-INCO Copernicus, [4], NSEE / E-Defence, [5] and currently the FUSEIS, [6], attempted to investigate and to provide efficient and rectifiable structural solutions.

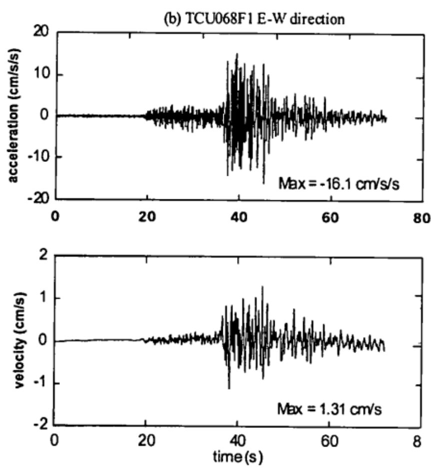
Consequently, in order to properly predict the inelastic capacity of steel structural systems a holistic view from the genesis of the earthquake phenomena through the geologic-geotechnical conditions is necessary in addition to all aforementioned factors should be absolutely related to the global and local structural behaviour. Obviously there is a "chain reaction" formatted by the earthquake engineering / engineering seismology - geotechnical earthquake engineering - steel structural design, and hence a multidisciplinary effort is needed in order to implement the inelastic analysis and design of the steel structural systems in a safe and economic way.

This paper, through the existing literature review, is focused upon the effect of the different loading history and the loading rate on the capacity of steel structural members. By using past earthquake damage knowledge bases, it attempts to illustrate the differences between the far and near source excitations. It also discusses the different inelastic behaviour under the loading conditions which could be further associated with the generally recognized seismic typologies (near field vs. far field).

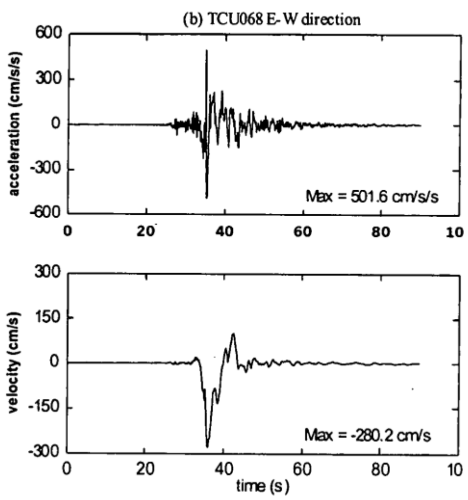
3. EARTHQUAKE EXCITATION CHARACTERISTICS ASSOCIATED WITH INELASTIC BEHAVIOUR

The ground motion and the structural behaviour, through the geologic and local site geotechnical conditions, form a part of an interrelation that could be addressed under a general view where a global source effect influences a local point as is the steel structure and its component elements. Obviously it is beyond the conventional soil-structure interaction, due to the fact that deals with the fault mechanism, depth, distance, magnitude, duration, local ground conditions, surface topography, directivity, radiation pattern, positioning of the structure as compared with the other ones and finally structural conformation and detailing. Therefore, an integrated geotechnical / structural expertise is needed in order to consider the source-soil-structure interaction. The analysis and design of the local point (e.g. level of a structure, element, joint) is strictly related with the aforementioned multiparametric factors which must be considered, otherwise the final result could be deficient.

Generally we distinguish two types of earthquake excitations, namely the far-source as well as the near-source earthquakes. The type of excitation, for a far and near field recording, is different as we can observe from figure 1, where the "921 Chi-Chi" Taiwan earthquake, 1999, is illustrated. Far–source earthquakes have longer duration, much more cycles than the near field ones, low velocity characteristics, an increased effect of soil conditions influence, while near-source excitations have a significant velocity pulse, with great values of velocity and velocity pulse duration, a reduced number of important inelastic cycles and acceleration duration, as well as a distinct long period profile as compared with the one coming from the local soil conditions.



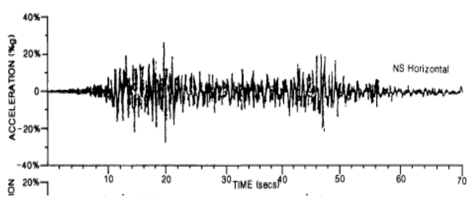
Far source earthquake
Epicentre distance: 157.80 Km
PGV/PGA = 0.08



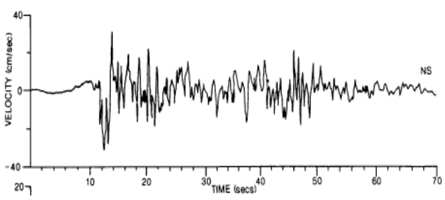
Near source earthquake
Epicentre distance: 0.49 Km
PGV/PGA = 0.558

Fig. 1: 921 Chi-Chi Earthquake, 1999 a) far source, b) near-source ground motion.

It is also important to present a benchmark ground motion from the Michoacan earthquake, Mexico 1985, in order to illustrate the soil effect of a pure far-source earthquake, Fig. 2. It is obvious the repetitive action, with many cycles as well as the importance of duration.



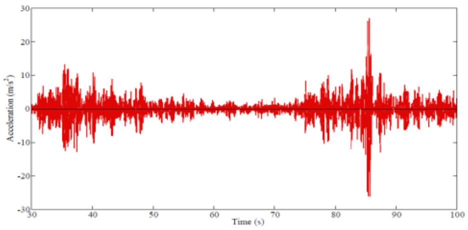
Acceleration ground motion

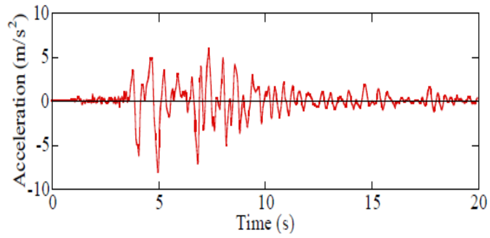


Velocity ground motion

Fig. 2: Michoacan earthquake, Mexico 1985.

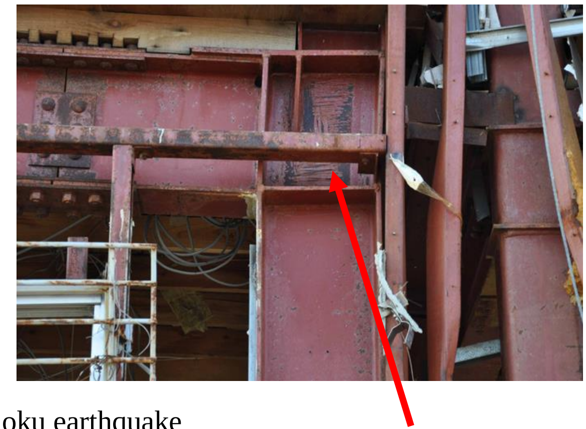
Consequently, not only the demand is going to be different, as defined from the input energy, but also the deformational capacity of the component elements of a structure. This stands particularly true as it was revealed from real earthquake events when in case of far-field earthquakes the cycle action with more inelastic cycles is the predominant one, producing stiffness and strength degradation (e.g. local buckling), while in case of near-field earthquakes the loading rate and the impulsive character of the loading are amongst the main influencing factors leading to brittle failures. For instance, taking into account two distinct earthquakes, the Tohoku, Japan, 2011, [7], as a far-field action, and the well-known Kobe earthquake, 1995, as a near-field seismic action, Fig. 3a, we can observe that for the first one the strongly repetitive cyclic action enabled dissipation mechanisms like flange and web local buckling and panel zone deformation, Fig. 3b, while for the second one brittle failures without any sign of deformation, Fig. 3c.





a) Tsukidate ground motion (NS), far-source

JMA Kobe record (NS), near source



Signs of web and flange local buckling

b) Damage from Tohoku earthquake

Signs of panel zone deformation

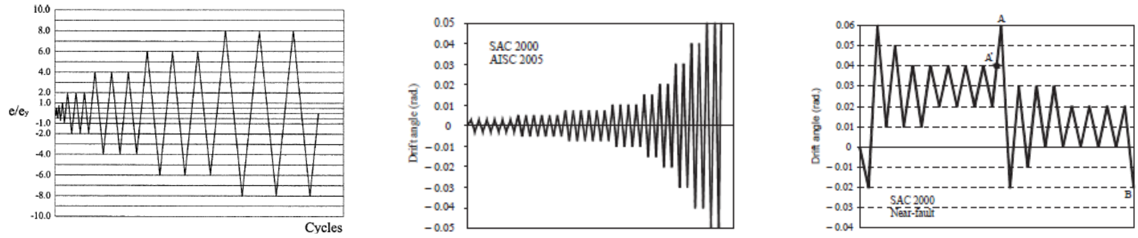
c) Damage from Kobe earthquake

Fig. 3: Differences in the damage in case of far and near source earthquakes.

4. LOCAL INELASTIC CAPACITY UNDER DIFFERENT LOADING ACTIONS

The same element or structure behaves differently under different actions. Obviously, as illustrated in the above paragraph, the steel elements, as a function of the seismic excitation, may respond distinctly developing ductile or brittle inelastic behaviour. The majority of studies were carried out investigating the inelastic demand, but only few experimental [8], [9], [10] and analytical studies, [11], [12], [13] are focused on the inelastic capacity. Recently, Lignos and Krawinkler by utilising an experimental database provided valuable equations related to the prediction of the ultimate rotation capacity, [13].

In order to capture the inelastic behaviour, different loading protocols were proposed and used, Fig. 4. However the majority of those ones were based on the predominant cyclic action, Fig. 4a,b, not considering the impulsive action and the strain rate effect; due to the increased velocity which strongly increases the yielding limit where brittle fractures are observed. In any case, currently the generally used protocols better simulate the far-source earthquakes. Krawinkler, [14] propose a testing protocol that takes into account the impulsive action, Fig. 4c. Also in this last case the increased loading rate was not considered. Therefore, towards this direction more research should be performed in order to develop new loading history and rate protocols, taking into account the duration through the effective number of cycles that produce damage, as well as a cycle counting using the time history of structural response.



a) ECCS recommendation, 1986 b) SAC 2000, AISC 2005 c) Near-source protocol, [14]

Fig. 4: Different proposals for loading protocols used in experiments.

Figure 5 outlines the experimentally measured inelastic rotation capacity of steel beams under different load-deformation actions [8]; one can remark the great differences from one to another protocol, hence it is absolutely necessary to develop action protocols in order to reliably calibrate the behaviour as defined by real earthquakes, and further on to reliably predict the available local ductility of steel elements. Otherwise the well-known value of 3% of plastic rotation is questionable.

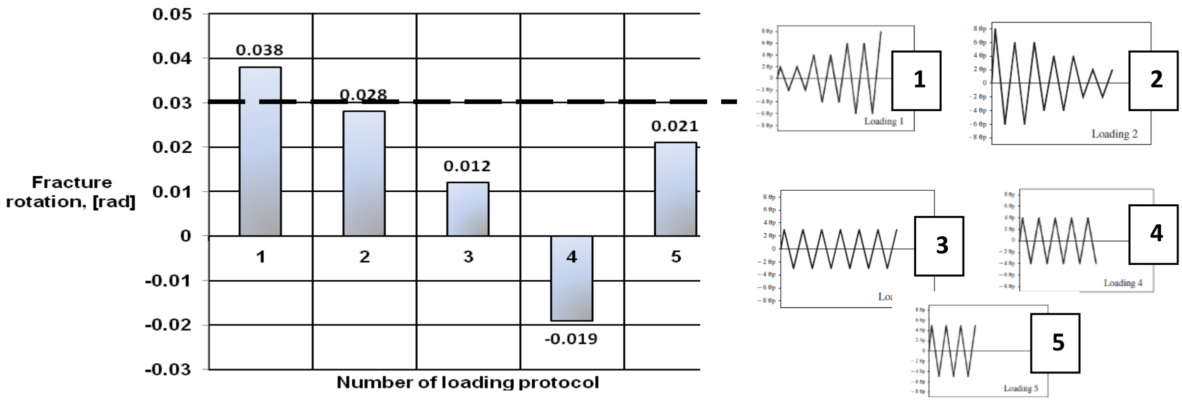


Fig. 5: Different proposals for loading protocols used in experiments

Moreover, beyond the absolute value of the fracture rotation also the number of cycles, until the fracture, is different. As a function of load-deformation relationship and the initial applied amplitude, the available rotation capacity strongly depends on the initial range of amplitude. Clearly, the task to codify, in real construction conditions, the prediction of the available local ductility seems to be difficult, although we could propose four ways of action, namely: (*i*) performance of microzonation studies for each earthquake prone zone or city, in a country providing the input data for the generalization of loading protocols after an extensive time history analysis, execution of a detailed geotechnical site investigation and characterisation study in the foundation area of the project, providing the accurate soil / rock mechanics input data, properties, coefficients and parameters for the appropriate selection of the foundation type and its analysis and design, (*ii*) proposal of different loading histories and procedures open to be selected by the designer, tailored on a project-by-project basis, and (*iii*) proposal of an envelope for all the cases, e.g. far / near source, local site geotechnical conditions, etc. The last case is the more conservative one. With regard to the loading rate, the increasing of the strain rate dramatically changes the cyclic behaviour of a joint, [9], Fig. 6a. It is important to remark that, as was revealed by the experimental tests carried out by El Hassouni et al, [9], more than 80% of the input energy was dissipated by the panel zone, while the beam rotation representing only approximately the 20% of the remaining ductility. Nevertheless, in the real construction conditions there are secondary beams, connecting the adjacent frames, thus the panel zone deformation is strongly constrained leading to the concentration of the inelastic action at the beam-column interface. The aforementioned total rotation could not be undertaken by the beam connection to the column as was demonstrated by the Northridge, 1994, and Kobe, 1995, earthquakes, developing brittle fractures, Fig. 6a. It should be underlined that the work carried out in [9] used the ECCS protocol not considering the impulsive character of the action and further on the specimens were subjected to a strain-rate value between 9 to 12 % s^{-1}. Instead, at real seismic events the level of strain-rate varies between 10% to 1000% s^{-1},[12]. In this direction more experimental and analytical work should be performed using new proposed protocols combined with high strain rate (as possible due to the experimental installation constraints) and also considering the real construction detailing (presence of the secondary beams, slab effect, stiffeners, hybrid beam-column use of different steel qualities, etc).

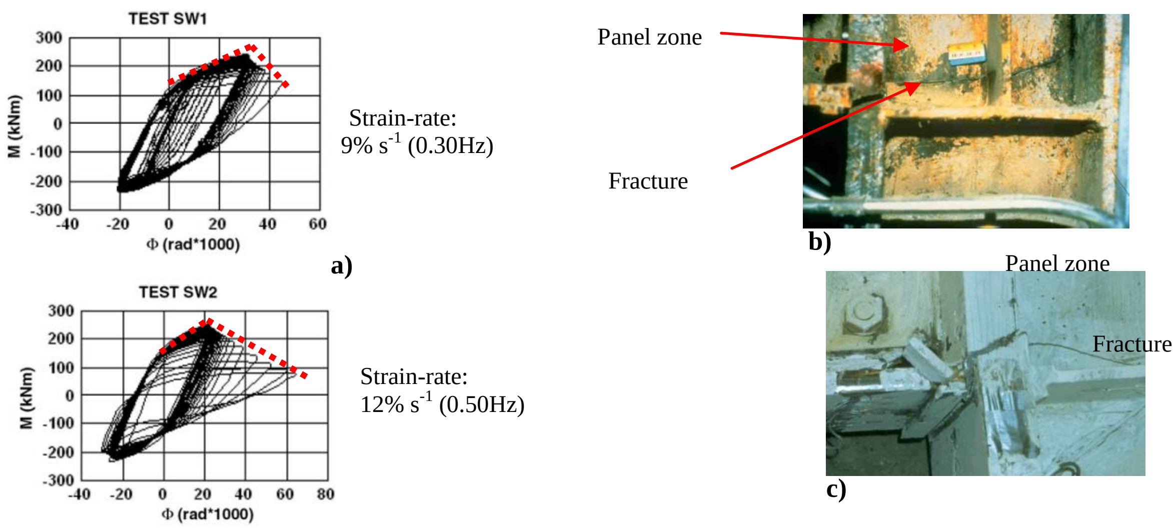


Fig. 6:. a) Behaviour of fully welded beam column specimen under strain-rate, [9] b) Northridge observed damage, c) experimentally produced damage [3]

5. CONCLUSIONS

The paper attempts to present the influence of the different earthquake type excitations on the available local ductility of steel structural elements; however, due to the difficulty of the structural interpretation of seismic data and inherent uncertainties related to them, it is focused on limited past earthquake events and further on the conclusions could not be generalized. Therefore, a tendency from the above mentioned earthquakes was that in case of far source seismic actions a predominant cyclic action was observed leading to the fracture due to a low cycle fatigue mechanism, while in case of near-source actions very few cycles having a predominant impulsive character associated with an increased velocity, which increases the yielding ratio, leads to a different fracture mechanism. A perspective towards the consideration of the inelastic design would be the development of new testing protocols, and further on approaching the topic from a multidisciplinary point of view. Finally, the new generation of performance based design codes should be more open providing only with the basic objectives and principles, also accompanying the basic code with recommendation guides focused on special topics targeting to the integrated source-soil-site-structure interaction analysis and design.

6. REFERENCES

[1] KRAMER S. "Geotechnical Earthquake Engineering". *Prentice Hall*, 1996.

[2] GIONCU V., MAZZOLANI F.M. "Earthquake Engineering for Structural Design". *London: Spon Press*, 2011.

[3] http://www.sacsteel.org/project/

[4] MAZZOLANI F.M. (ed), 2000. "Moment Resistant Connections of Steel Frames in Seismic Areas", *E&FN SPON, Taylor & Francis Group*, 2000.

[5] http://peer.berkeley.edu/events/2013/nees-edefense/

[6] http://fuseis.ntua.gr/

[7] EERI Special Report. Performance of Engineered Structures in the Mw 9.0 Tohoku, Japan, Earthquake of March 11, 2011. January 2012.

[8] JIAO Y., YAMADA S., KISHIKI S., SHIMADA Y. "Evaluation of plastic energy dissipation capacity of steel beams suffering ductile fracture under various loading histories". *Earthquake Engineering and Structural Dynamics*, Vol. 40, Issue 14, 2011 pp. 1553-1570.

[9] El HASSOUNI A., PLUMIER A., CHERRABI A. "Experimental and numerical analysis of the strain-rate effect on fully welded connections". *Journal of Constructional Steel Research*, Vol. 67, No. 3, 2011, pp. 533-546..

[10] UANG C.M., YU Q.S., GILTON C.S , 2000. "Effects on loading history on cyclic performance of steel RBS moment connections", *Proc. 12th World Conference on Earthquake Engineering (12 WCEE 2000)*, 2000, cd paper 1234.

[11] ANASTASIADIS A., MOSOARCA M., GIONCU V., 2012. "New aspects concerning the ductility of steel members", *Proc. Int. Conference on Behaviour of Steel Structures in Seismic Areas (STESSA 2012)*, 2012, pp. 455-461, Santiago.

[12] GIONCU V., MOSOARCA M., ANASTASIADIS A. "Local ductility of steel elements under near-field loading". *Journal of Constructional Steel Research*. Vol. 101, 2014, pp. 33-52.

[13] LIGNOS D., KRAWINKLER H. "Deterioration modelling of steel components in support of collapse prediction of steel moment frames under earthquake loading". *Journal of Structural Engineering*. Vol. 137, 2011, pp. 1291-1302.

[14] KRAWINKLER H. "Loading histories for cyclic tests in support of performance assessment of structural components". *3rd International Conference on Advances in Experimental Structural Engineering*. San Francisco, 2009.

Τάσεις και ανάγκες για πρόβλεψη της ανελαστικής ικανότητας των μελών από δομικό χάλυβα λαμβάνοντας υπόψη τις διαφορές στις σεισμικές συνθήκες φόρτισης

Άνθιμος Σ. Αναστασιάδης
Δρ. Πολιτικός Μηχανικός
GeoStatic Partnership (www.GeoStatic.eu)
Τ. Παπαγεωργίου 10, 54631, Θεσσαλονίκη
e-mail: anstasiadis@geostatic.eu

Τζανετής Ι. Βογιατζής
Διπλ. Πολιτικός Μηχανικός, MSc, Υποψ. Διδάκτωρ
GeoStatic Partnership
Τ. Παπαγεωργίου 10, 54631, Θεσσαλονίκη
e-mail : voghiatzis@geostatic.eu

Κωνσταντίνος Ι. Σαχπάζης
Δρ. Γεωτεχνικός & Πολιτικός Μηχανικός
GeoStatic Partnership
Διονυσίου 29, Ίλιον 13122, Αττική
e-mail: sachpazis@geostatic.eu

ΠΕΡΙΛΗΨΗ

Η ανελαστική συμπεριφορά των δομικών στοιχείων εξαρτάται έντονα από το είδος της σεισμική διέγερσης. Επιπλέον η πλαστιμότητα, τόσο σε τοπικό όσο και σε καθολικό επίπεδο, εξαρτάται άμεσα από το ιστορικό καθώς και τον ρυθμό φόρτισης. Μετά από τον σεισμό του San Fernado, 1971, καθώς και τους σεισμούς του Μεξικό, 1985, και εν συνεχεία από τους εξαιρετικά ιδιαίτερους σεισμούς του Northridge, 1994, και του Kobe, 1995, διαπιστώθηκε και καταγράφηκε η σημαντική διαφορά που προκαλούν σε επίπεδο συμπεριφοράς κατασκευής οι σεισμοί εγγύς και μακρινού πεδίου. Η παρούσα εργασία, λαμβάνοντας υπόψη την υπάρχουσα βιβλιογραφία, και θεωρώντας ότι η ανάλυση και ο σχεδιασμός απαιτούν διεπιστημονική δομοστατική και γεωτεχνική προσέγγιση, εξετάζει την επίδραση των διαφορετικών ιστορικών φόρτισης στην ανελαστική συμπεριφορά των μεταλλικών δομικών στοιχείων. Επιπλέον, επιχειρεί να προσεγγίσει τον τρόπο με τον οποίο μπορεί να εκτιμηθεί η διαθέσιμη τοπική πλαστιμότητα κάτω από τις προαναφερόμενες συνθήκες.