International Journal of Engineering Research
Volume No.5 Issue: Special 3, pp: 725-730
ISSN:2319-6890)(online),2347-5013(print)
27-28 Feb. 2016

Seismic Performance of Composite Moment-Resisting Frames: State of the Art

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Abstract : ***Owing to high strength and good ductility, steel structures are widely used in the construction of building frames in seismically active areas. This paper reviews the state-of-the-art in testing, finite-element analysis and design of composite structural systems. Development of guidelines and recommendations of beam–column connections and moment frames are presented and a future research on composite structural systems is provided. In this paper, the effect of composite action on the ductility performance of the connections is reviewed through a series of large size experimental and analytical studies of beam-to-column subassemblies. The studies presented in this paper highlights important behavioral observations and trends, some of which point towards the need for further consideration and refinement of current design procedures. The reference structure as well as the design procedures and assumptions adopted are discussed. This paper briefly describes some past experimental and analytical research on traditional connections relevant to the innovative types of connection models to be developed. This paper does not intend to provide a complete and systematic literature search on the topic but rather just present some examples of how connections have been investigated in the past.***

Keywords moment resisting frame, plastic hinges, connection models, finite element analysis.

1. Introduction

Moment resisting frames are used as part of seismic force resisting systems in buildings designed to resist earthquakes with substantial inelastic energy dissipation. Beams, columns, and beam-column connections in moment frames are proportioned and detailed to resist flexural, axial, and shearing actions that result as a building sways through multiple inelastic displacement cycles during strong earthquake ground shaking. Moment resisting frames offer a flexible solution to the user of the buildings, especially for the internal arrangement and the exploitation of the buildings. When sufficient stiffness and strength with regard to lateral forces are achieved, such frames offer a structural solution, which can resist lateral loads. In seismic regions, properly designed moment resisting frames are the best choice regarding the available ductility and the capacity to dissipate energy. The principal advantage of moment frame structures is that they do not have structural walls or vertically oriented diagonal braces. They therefore provide architectural freedom in design, permitting open bays and unobstructed view lines. The tradeoff for these benefits is that moment frames can be more costly to construct than braced frame or shear wall structures. The added cost results from the use of heavier sections in the moment resisting frames, requiring increased steel usage and more labor intensive connections than is common in braced structures. However, moment frames typically impose smaller forces on foundations than do other structural systems, resulting in somewhat more economical foundation systems.

Steel-concrete composite systems have seen widespread use in recent decades because of the benefits of combining the two construction materials. Reinforced concrete is inexpensive, massive, and stiff, while steel members are strong, lightweight, and easy to assemble. In decks, composite systems eliminate the need for formwork. In columns, two systems are commonly used; steel reinforced concrete, where a steel section is encased in concrete and concrete filled tubes. One important advantage of composite systems is that construction is accelerated through separation of trades.

The inelastic behavior of composite members and systems, which is particularly important in limit state calculations for earthquake resistant design, is not yet thoroughly understood. As a result, design provisions for composite structures have generally been extrapolated from provisions for traditional reinforced concrete or steel structures and the recent development of specifications addressing composite construction are increasingly providing engineers with guidance on the analysis and design of composite members and systems. Steel-concrete composite framed buildings are highly efficient structural systems due to their stiffness, strength and ductility. Steelï concrete composite structures are subjected to various kinds of dynamic loadings,such as earthquakes, wind, machine-induced vibrations. Such systems allow also adequate seismic performance nevertheless their application in seismic area is prevented by the lack of experimental information and design rules, especially about joints. There is a need for assessing the key parameters influencing the seismic performance of composite moment frames with typical geometric and loading configurations.

2. Problem Statement

For the study a reference structure is selected such that it can be used as a basis for parametric variations. The structure consists of a five-storey composite steelï concrete office building. In plan, columns are spaced at 9 m in both directions Fig.1. With due account of column inertia, lateral resistance is provided by

ISSN:2319-6890)(online),2347-5013(print)
27-28 Feb. 2016

composite moment frames in one direction whilst the other plan direction is assumed to have a braced system. The floors consist of 120 mm thick composite slabs of the re-entrant (dovetail) profile with 1 mm thick steel deck supported by secondary beams spaced at 3 m.

Finite Element Modeling: After the elastic frame design, a nonlinear static analysis is performed to assess the actual resources of ductility of the adopted reference structural system. Among the various models available for the analysis of composite structures frame models allow the obtainment of significant information at reasonable computational cost compared to more sophisticated two-dimensional and three-dimensional finite element models.

This analysis was carried out by assembling a lumped plasticity model. Elastic frame elements were adopted for columns and beams with plastic hinges at the ends.

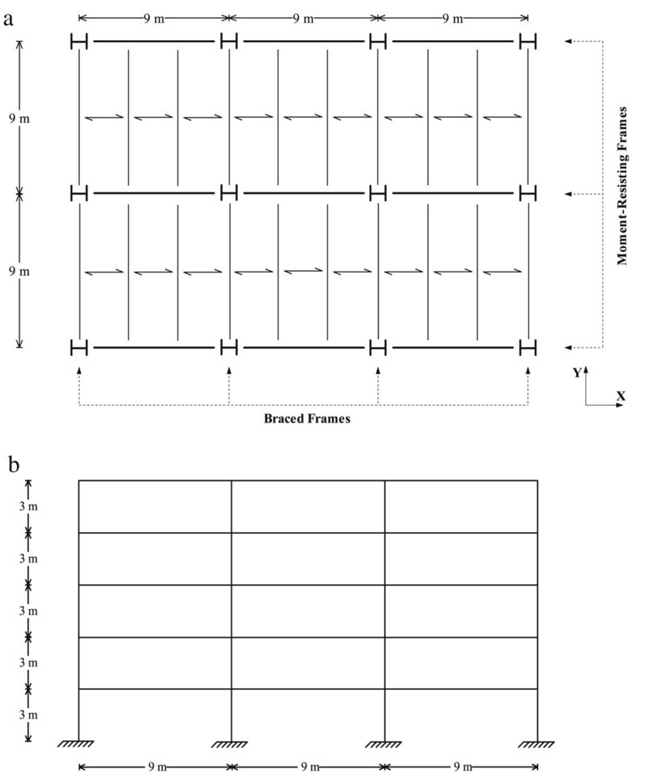

Fig. 1. Structural arrangement for the reference structure: a) Plan configuration, (b) Elevation of moment-resisting frame.

3. Literature Review

Numerous research works have been proposed in the literature though a handful research works that deals with nonlinear analysis of composite moment resisting frames is briefly reviewed here.

A.Y. Elghazouli_, J.M. Castro, B.A. Izzuddin,[1] examines the seismic performance ofcomposite steelï concrete moment-resistingframes. A number of studies are carried out in order to assess the influence of key parameters, related to the structural configuration as well as design andloading considerations, on the inelastic seismic behavior. Several sensitivity and parametric investigations are undertaken using an advanced analysis program that accounts for material and geometric nonlinearities. Particular emphasis is given to composite frames designed according to the provisions of the European seismic code, Eurocode 8. The validity of employing simplified nonlinear-static loading approaches is evaluated by comparison against the results of incremental dynamic time-history analysis. Natural earthquake acceleration records, which are specifically selected and adjusted for compatibility with the adopted design spectrum, are utilised for this purpose. In terms of frame configuration, it is shown that the span of the composite beam, the extent of gravity loading and the number of stories can all have significant implications on the actual inelastic response characteristics of the structure. Moreover, several design assumptions and decisions, such as those related to the behavior factors, drift considerations, moment redistribution and panel zone contribution, can also have a direct impact on the resulting performance. The studies presented highlight important behavioral observations and trends, some of which point towards the need for further consideration and refinement of current design procedures. The suitability of pushover analysis with triangular loading, in comparison with the uniform pattern, is supported by the overall structural response as well as local inter-storey drift distributions.

Marisa Pecce ,Claudio Amadio, Fernando Rossi, Giovanni Rinaldin, [7] presented the numerical results of a non linear analysis of a steel-concrete composite MRF in order to evaluate the effect on the seismic performance of the rotational capacity of plastic hinges and deformability of beam-column joints. In particular, in the modeled frame, extracted from a building designed according to the rules of Eurocode 4 and 8, a lumped plasticity approach was adopted and the moment-rotation relationship of the plastic hinges was determined by multiplying the moment-curvature relation of the cross-section for the plastic hinge length. The expressions of this latter parameter were selected from those available for the R.C., steel and steel-concrete composite structures. The results obtained using these equations are largely different and have a direct influence on the overall ductility of the structure, highlighting the need of further experimental and numerical data to assess this knowledge for the composite structures. As regards the influence of the joint modeling, it was observed that, though the resistance hierarchy was respected according the capacity design approach, the deformability of the full strength beam-column joint modifies the overall stiffness and the global nonlinear response of the frame. This effect depends on the deformability of web panel, the steel parts in tension or compression, the shear connection between the steel beam and the RC slab and its interaction with the

ISSN:2319-6890)(online),2347-5013(print)
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column. The joints deformability also affects the behavior factor (q) and the over-strength of the structure, although the obtained overall values were not much deviate (about 12% for q and 23% for the over-strength) from those assumed in the design. Thus, the study confirms that for a correct evaluation of the nonlinear response of a steel-concrete composite framed building is essential to correctly define the deformability of the joints and the plastic rotational capacity of beams and columns, aspects that in the current standard rules are not properly defined for the examined structural system.

C. G. Bailey,D. B. Moore,[24] presents the development of a new design method for calculating the performance of steel framed buildings, with composite flooring systems, subject to fire. This design method is based on the results from a series of full-scale tests on an eight-storey steel framed building, together with associated theoretical and further experimental investigations. The results from this work show that the performance of composite steel deck flooring systems in fire is under-utilized in current design procedures. From these observations a simple design method is developed that is based on a holistic, rather than an elemental, approach.

This allows the various interactions between the components of a composite slab, supported by a grillage of steel beams, to be taken into account, producing cheaper and more innovative, site-specific, fire-engineering solutions.

L. Song, B.A. Izzuddin, A.S. Elnashai and P.J. Dowling,[9] presents a new method for the nonlinear analysis of steel frames subject to fire and explosion loading conditions. The proposed method subsumes conventional nonlinear analysis in that it can be applied to the two cases of fire and explosion loading in isolation and, more significantly, within the same analysis. The resulting integrated approach can therefore be used to study the behavior of steel members and frames subject to scenarios of explosion loading followed by fire, effectively enabling the influence of explosion on the fire resistance to be evaluated. The study describes the component beam-column formulations and discusses their incorporation within an adaptive analysis framework, which is largely responsible for the considerable efficiency of the proposed method. Details of the required elasto-plastic material models are finally presented, including the adopted models for steel subject to elevated temperatures, creep and high strain-rates.

Adrian Ciutina,[10] presented the seismic responses of two composite structures, considering time-history dynamic analyses based on the Romanian Vrancea 1977 accelerogram and two artificial accelerograms consistent with the European C-soil spectrum. The structures have been pre-designed in a usual manner by elastic push-over analyses, assuming their location in a seismic zone of maximum intensity 0.35g. The dynamic analyses reveal the applicability of the simulated joints for the considered accelerograms, scaled in order to correspond to the design ground acceleration. The results are given in terms of required elasto-plastic rotations, maximum inter-storey drifts, behavior factor q and the performance factor ḍ. For the beams and columns, appropriate fiber finite elements are used. The beam-to column joint behavior is integrated into the structural modeling by means of a sophisticated finite element which models with good accuracy the experimental behavior of joints.

Xiangming Zhou , Guoqiang Li,[15] investigated seismic behavior of steelï concrete composite high-rise buildings, composed of external steel frames and internal concrete tube , with rectangular plan. A macro-element based model is established for seismic analysis of composite high-rise buildings aiming at predicting their global responses under earthquakes. By employing this macro-element based model, natural frequencies and vibration modes, storey and inter-storey drifts, overturning moments and storey shear forces of composite structures, induced by earthquakes, are able to be obtained with much less computation time and cost compared with using micro-element based analytical models. To validate its efficiency and reliability, the macro-element based model is employed to analyze a 1/20 scaled-down model of a 25-storey steelï concrete composite high-rise building subjected to simulated earthquakes with various intensities through a shaking table. Natural frequencies and storey drifts of the model structure are obtained from numerical analyses and compared with those from shaking table test results. It has been found that the calculated dynamic responses of the composite model structure subjected to minor, basic, major and super strong earthquakes agree reasonably well with those obtained from experiments, suggesting that the proposed macro-element based model is appropriate for inelastic time-history analyze for global responses of steelï concrete composite high-rise structures subjected to earthquakes with satisfactory precision and reliability. This research thus provides a practical model for elastic and inelastic deformation check of high-rise composite buildings under earthquakes.

Oreste S. Bursi, Fei-Fei Sun, Stefano Postal,[3] investigated the seismic performance of moment-resisting frames consisting of steelï concrete composite beams with full and partial shear connection. To this end, six full scale composite substructures with headed stud shear connectors have been tested and the corresponding inelastic responses to both monotonic and variable reversed displacements have been investigated. Three dimensional finite element models of the substructures set with the ABAQUS code and based on shell elements are established in order to evaluate different modeling assumptions and local effects; and to calibrate aone-dimensional model conceived with the Drain-3DX code relying on layered beamï column elements. The one-dimensional model is then exploited for a parametric study on two four-storey frames by means of non-linear dynamic analyses. The analyses have revealed that composite frames with a low shear connection degree of about 0.4 perform as well as their companion frames with full shear connection under severe seismic loads. Nonetheless, the shear connection degree should be high enough in order to protect shear connectors in the central part of beams from failure. Although their equivalent damping is not very high, shear connectors could reduce the ductility demand on other parts of a composite frame, such as beam ends or partial strength beam-to-column joints. This design option could provide a further means to achieve a favorable performance of a composite moment-resisting frame, in addition to the benefit of cost reduction.

Alessandro Zona; Michele Barbato; and Joel P. Conte,[16] examines the use of beams with deformable shear connection in the analysis of frame structures raises very specific modeling issues, such as the characterization of the cyclic behavior of the deformable shear connection and the assembly of composite beam elements with conventional beamï column elements. In addition, the effects on the dynamic response of SCC frame structures of various factors, such as the shear connection boundary conditions and the mass distribution between the two components of the composite beam, are still not clear and deserve more investigation. The object of this study is to provide deeper insight into the natural vibration properties and nonlinear seismic response behavior of SCC frame structures and how they are influenced by various modeling assumptions. For this purpose, a materially nonlinear-only finite-element formulation is used for static and dynamic response analyses of steelï concrete frame structures using composite beam elements with deformable shear connection. Realistic uniaxial cyclic constitutive laws are adopted for the steel and concrete materials of the beams and columns and for the shear connection. The resulting finite element model for a benchmark problem is validated using experimental test results from the literature for quasi-static cyclic tests. The paper then focuses on the numerical simulation, based on various modeling assumptions, of the eigen properties and seismic response of a realistic two-dimensional five-story two-bay moment resisting frame made of steel columns and SCC beams and designed according to the Eurocode. It is found that the inclusion of the deformability of the shear connection in the finite-element model has a significant effect on the global dynamic response of SCC frame structures. In modeling this type of structures by using frame elements with deformable shear connection, a proper representation of the shear connection boundary conditions for all composite beams is crucial for accurate response simulation.

4. Research Objectives

1] A simplified procedure for estimation of global and local seismic demands is developed to facilitate decision making in the conceptual design process.

2] The research is directed specifically towards the improving the seismic behavior of composite moment resisting frame structures, but is intended to be also a contribution to progress in the development and implementation of performance-based seismic engineering.

3] The expectation is that on the completion of all these studies, significant additions will have been made to the knowledge base needed to understand the behavior and to predict the response of typical composite moment resisting frame structures under ground motions with different characteristics and intensities. This improved knowledge base should permit improved design and evaluation of composite moment resisting frame structures within the context of performance based seismic engineering.

4] Evaluate the range of inter story drift demands that can be expected in composite moment resisting frame structures under different types of ground motions and at various hazard levels.

5] Appraise the effects of analytical models of various complexities on seismic demand predictions.

6] Quantify the effects of strength and stiffness deterioration on seismic demands.

7] Identify and quantify all issues that may have a significant impact on seismic performance.

8] Evaluate the effects of connection fractures on seismic performance.

9] Assess the feasibility of using partially restrained connections as alternatives to welded rigid connections.

10] Evaluate the effect of the rotational capacity of plastic hinges and deformability of beam-column joints on seismic performance.

5. Research Methodology

The nonlinear static (pushover) analysis is actually a very important tool for evaluating the performance of structures in seismic areas. However, the application of the method is not equally established for all type of structures. In the case of steel and concrete composite framed constructions, there is little information on the ductility (plastic rotational capacity) that can be assigned to the elements. This problem is particularly complex in the case of composite beams that have a strongly asymmetric behavior at sagging or hogging regions furthermore are affected by uncertainty on the determination of the effective width and behavior of the beam-slab connection.

The use of nonlinear-static, or pushover, analysis for seismic assessment and design has increased significantly in recent years. It can be employed to assess the overall capacity and stability, and to identify the likely plastic mechanisms and associated dissipative regions. The attractiveness of pushover analysis stems mainly from its relative simplicity, in terms of modeling and computational demands as well as interpretation of results, in comparison with nonlinear dynamic analysis. The nonlinear-static behavior of a typical composite frame is firstly assessed by comparing the response obtained from triangular and uniform pushover loading patterns. The validity of adopting nonlinear-static approaches for this type of structure is evaluated by comparison against the results of incremental dynamic time history analysis.

The design philosophy for composite moment resisting frames adopted by building codes discourages the formation of plastic hinges in the clear span portion of columns, while encouraging the formation of hinges in beams and, to a more limited extent, in beam-column joints. Therefore it would be interesting to analyze the rotational capacity evaluated by means the product of the plastic curvature of the section and the plastic hinge length.

Anyway this approach allows taking into account of the type of section, in this case composite beams (under sagging and hogging moment) and columns. It is clear that the global response accuracy may be compromised if a wrong calibration of the moment-curvature relationship or plastic hinge length is done. Therefore, particular attention must be reserved for the estimation of the moment-curvature diagrams, even in the presence of axial load and in the prediction of an equivalent plastic hinge length so as to define a rotational ductility close to the real one.

Thus, accurate modeling of random cyclic inelastic response of beams in composite moment resisting frames is essential for accurate predictions of frame response. When designing a composite moment resisting frames to resist lateral loads, beams are not usually designed for composite action.

Nonetheless, significant composite action can exist due to shear studs that are provided to transfer diaphragm forces or to provide lateral support for the beams. This composite action can have an important effect on the lateral strength and stiffness of the frame, on the natural periods of vibration of the frame, and on the local behavior at beam-column joints.

A nonlinear static analysis is performed to assess the actual resources of ductility of the adopted reference structural system. Among the various models available for the analysis of composite structures **frame models** allow the obtainment of significant information at reasonable computational cost compared to more sophisticated two-dimensional and three-dimensional finite element models. **This analysis was carried out by assembling a lumped plasticity model. Elastic frame elements were adopted for columns and beams with plastic hinges at the ends.** The advantage of this modeling is that it allows working primarily with elastic elements which are less expensive from the computational point of view, leaving into few points the concentration of the material non-linearity. The validity of using nonlinear-static approaches for this type of frame is evaluated by comparison with dynamic time-history analysis, using earthquake records which are carefully selected and adjusted for compatibility with the design spectrum. The resulting finite-element model for a benchmark problem is validated using experimental test results from the literature for quasi-static cyclic tests. A number of numerical studies are then carried out in order to assess the influence of key loading, geometric and design parameters on the response of composite frames.

6. Probable Research Outcomes

An automated analysis and design of composite moment resisting frame structure will be done by employing Finite Element Method based computer softwares like Ansys, Abacus, SAP and Etabs. An analytical model will be prepared to carry out numerical analysis for satisfactory fulfillment of above mentioned research objectives. Generic Algorithm, Fuzzy Logic Techniques and self developed Finite Element software programmes may be employed if required. The results will be given in terms of 1] Elasto-plastic rotations.2] Maximum inter-storey drifts. 3] Behavior factor q.4] Seismic Response Factor q.5] P-delta Effect.6] The moment-curvature relationships of beams and columns composite sections.7] Parametric analysis on the influence of the plastic hinge length.8] Comparison of global nonlinear response to vary plastic hinge length: a) Modal distribution; b) constant distribution9] Comparison of the global nonlinear response considering rigid or deformable joints.10] Pushover curves with rigid and deformable flanged joints:a) Modal distribution;b) Constant distribution of the seismic forces.11] Variation of the behavior factor q and over-strength factor: a) Modal distribution; b) Constant distribution.

7. Summary and conclusions

During the past decade there has been a significant amount of research on the behavior and design of composite structural joints and frame systems for seismic loading. There has led to the development of new technologies and guidelines for composite structural systems. This paper has summarized representative recent research projects focusing on four situations of structural systems: testing and finite-element analyses of beam-to-column connections

and subassemblies; testing of moment frames and finite-element analyses; seismic design studies and analyses of moment frames; and development of guidelines and recommendations of moment frames. However, from the existing research results of composite structural systems, specific areas in update seismic design provisions of the composite frame structures are still likely to be developed in the coming decade include:

(1) Many researches on the composite structure systems mainly in composite joints, but the overall frame structure is less. The actual frame design follows the óśstrong columnï weak beamőô philosophy is whether real guarantee in structural damage that need for further study.

(2) The test and study on composite frame are mainly the non-braced frame structure, while seismic performance and comprehensive benefits of composite braced frame structure will be likely for future study.

(3) The finite-element analysis on the composite connections and overall frame structure should be further enhanced. It may not practicable to do a lot of full-scale tests due to the restrictions of laboratory and test equipment and economic can be used as an effective means of research. But the finite element method cannot completely simulate effects of earthquake, especially under rare earthquake, the need for further study.

(4) The seismic design theory of composite frame structure is required to be further improvement. In current, the United States and Japan have developed the seismic design guidelines of structural systems, but they are based on bearing capacity design, performance-based seismic design has to be studied.

(5) Composite frame structure consisting of material strength, they included: concrete strength, reinforcement strength and structural steel strength. However, they are mostly normal strength, so the performance of composite frames consisting of high-strength concrete of high strength structural steel will need to be explored and study.

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