Modelling techniques of composite joints under cyclic loading

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Abstract

This paper presents a finite element model to simulate the behaviour of composite steel-concrete joints subjected to cyclic loading. The composite joint is a corner column connected to by two beams and a concrete slab. The beam to column connection uses end-plates and the slab is connected to the beams via shear studs. This paper concentrates on investigating efficient modelling techniques for such a composite joint. A three-dimensional model has been used. The model adopts model substructuring techniques and composite action modeling methods. The efficiency and suitability of the model has been examined under cyclic loading conditions. The results of the analysis have been compared with other published results. It is concluded, form the $M-\theta$ hysteresis curves, that the proposed model is able to capture the behavior of composite joint in positive bending with acceptable accuracy. However, the model did not achieve as good a result in the case of negative bending. The investigation also confirmed that the use of model sub-structuring is capable of modeling demanding problems and can provide moderate saving in computing time.

Keywords: finite element, modelling technique, composite joints, cyclic loading, steel connection

1 Introduction

The recent design of composite joints allows the composite action between concrete and steel to be considered, offering benefits for the strength and stiffness for structural beam to column joint system. The composite joints can be designed as ‘partial strength’ to meet serviceability criteria while remain economical. Following the 1994 Northridge earthquake, the importance of providing sufficient ductility for moment resisting connections has been highlighted in the seismic design of steel frames. Meanwhile, a series of investigations have been carried out for improvement of traditional moment resisting connections. Although there is an increasing interest in application of the composite joints in seismic design, there are still limited recommendations in recent design codes (Eurocode 8 2003; AISC 2005) with this type of connections.

Over the past two decades, the full-scale experimental studies in Europe (Mazzolani 1996; Plumier 1999; Aribert 2000; Vasdravellis 2008) have developed further understanding for the cyclic behaviour of the composite joints. Although experiments yield direct results based on the reliable measurements, it is not possible to reveal every aspect of the tested sample, involved with a large number of variables. Moreover, time consuming and costly experimental work are limited for providing parametric study for practical design work. As a useful tool to analyse structural behaviour, the FE (finite element) modelling can be used to offer detailed information unable to obtain directly.
from the experimental measurements. However, it depends on the efficiency of adopted algorithms in capturing the deformation, plasticity and contact compatibility of the structural components. Due to the varied components and complicated interactions included in the composite joint system, some doubts from early researchers (SSEDTA 2001) arise about the reliable modelling of composite behaviours. However, the recent progresses in computer hardware and advanced numerical algorithm have provided improvements for rigorous analysis that can take into account almost all the possible sources of nonlinearity. Thus, finite element analyses have been taken by contemporary researchers to further study the behaviour of the composite joint as shown in Table 1. When subjected to cyclic loading, the composite joint exhibits different load transfer under negative bending and positive bending, corresponding to different excursion of hysteresis loops. Previous studies have been confirmed finite element solution as a reliable means to simulate monotonic behaviour of the composite joint. However, there are few reports that discuss modelling the cyclic behaviour and its evolution. This paper reports on a study that uses finite element modeling techniques to better describe the behavior of the composite joint under cyclic loading.

<table>
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<tr>
<th>Researcher</th>
<th>FE program</th>
<th>Modelling of composite action</th>
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<tr>
<td>Ahmed (1996)</td>
<td>ABAQUS v. 5.3.1</td>
<td>Joint elements between shear stud and reinforcement</td>
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<td>Kattner (2000)</td>
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<td>Salvatore (2005)</td>
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<td></td>
<td>ADINA v.8.0.2</td>
<td>Actual modelling of shear studs as only the nodes at the front side connected to the concrete slab with rigid connection using *TIE option</td>
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<tr>
<td>Fu (2007)</td>
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<td>Gil (2008)</td>
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<td>Vasdravellis(2008)</td>
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<td>Dabaon (2009)</td>
<td>ANSYS v.4.4</td>
<td>Spring elements between concrete slab and steel beam</td>
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2 Finite element model

As composite joint system consists of different components with nonlinear properties, the computational costs are expected to be very high if all these details are considered. Meanwhile, the finite element analysis may become much more difficult due to longer load steps if the cyclic loading procedures are actually taken. For these reasons, appropriate simplifications need to be adopted by means of recent modelling techniques to avoid excessive complexity involved in finite element modelling. The key points described here include: modelling of composite action, modelling of façade (or secondary) beam and the use of sub-structuring. The 3-D nonlinear finite element models in this study were developed with the use of the ANSYS finite element package.

2.1 Modelling of composite action

The interaction between steel and concrete is related to the load-slip relationship, which varies with the type of shear connector. The load induced slip between the steel and concrete can be obtained through pull out test, suggested by the recent Eurocode (Eurocode 4). There are also many analytical models have been proposed in the literature to characterize the load-slip relationship, in which the exponential model (Yam 1968; Ollgaard 1971) has been extensively adopted by other researchers. This is given in Equation 1 as below.

\[
Q = Q_{\text{max}} \left(1 - e^{-\alpha s}\right)^\beta
\]  

(1)
Where, $Q_{\text{max}}$ denotes the ultimate capacity of the shear connector, $\alpha$ and $\beta$ are constants determined by experiment. Typical load-slip relationships with varied value of $\alpha$ and $\beta$ are plotted in Figure 1.

There are two main methods used to model the composite actions between the shear studs and the concrete slab. The first uses virtual model of the studs connected to the concrete via shared nodes. The second used spring elements to model the composite action. Figure 2 shows an example of a spring element modelled using its force displacement behaviour. The behaviour is typically derived from Equation 1 or from experimental results. A list of various approaches taken by other researchers was provided in Table 1. The use of spring element can simplify the finite element model, and can result in better convergence of solutions. In this study, the longitudinal composite action was modelled with nonlinear spring element (COMBIN39, ANSYS), which is defined by a generalized force-deflection curve, as shown in Figure 2. The adjacent steel beam nodes and concrete nodes are coupled in vertical direction to neglect the effects of uplift.

2.2 Modelling of façade beam

For design of a ductile composite moment frame, Eurocode 8 provides two conditions as to avoid early buckling of steel section and early crushing of the concrete slab when the composite joint subjected to bending. The force transfer mechanisms corresponding to the composite joint under negative and positive bending are shown in Table. 2. For these mechanisms, Eurocode 8 differs from Eurocode 4 (for predominantly static loading) in terms of the description of negative bending behaviour and the application of façade beam (transverse beam). Mechanism 1 and Mechanism 2 relate to positive bending induced compression on the column, which are achieved through direct bearing of the steel section and concrete struts with 45° on the column side. Mechanism 3 deals with the use of façade beam with effective anchorage of rebar to transfer moment. As the façade beam is fixed to the column, the forces transferred from the concrete slab may cause local bending, shear and torsion of the façade beam, especially for exterior composite joint. This action in turn constitutes a contribution to the overall behaviour of the composite joint system (Eurocode 8 2003).

The façade beam can be modelled in the identical manner as the main beam. To balance accuracy and efficiency, however, the computationally cheap beam element with multi-point constraint (MPC) was adopted in present study (ANSYS Swanson Analysis Systems).

The multi-point constraint algorithm is powerful for enforcing compatibility at an interface, which improves the solution efficiency and simplifies the modelling of transitions from different types of elements. Taking advantage of this approach, consistent connectivity between the solid elements (refers to the column) and beam elements (refers to the façade beam) is used in this study.
Table 2. Force transfer mechanisms of analytical model (interior joint) suggested by Eurocode 8

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<th>Mechanism 1</th>
<th>Mechanism 2</th>
<th>Mechanism 3</th>
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<td>Negative bending</td>
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2.3 Sub-structuring models

In the analysis of complicated finite element models, the modern sub-structuring technique has become one of the most efficient ways to sub-divide the problems into several smaller parts. Solutions can thus be obtained more efficiently. The sub-structures are analysed individually resulting in condensed matrix elements, which are named ‘super-element’ in ANSYS. At the end of the condensation, the matrix equations evolve as a set of master degrees of freedom (DOF) to define the interface between the super-element and other elements. Then the followed solution of the matrix equations can be expanded in terms of master DOF of each substructure.

Based on the sub-structuring principles, a typical substructure analysis consists of three steps or passes, including generation pass (creating the super-element), use pass (using the super-element) and expansion pass (expanding results within the super-element), as shown in Fig. 3. As the column parts and composite beam outside the composite joint are in linear portion of the model, the former parts are sub-structured in this nonlinear analysis, while the latter parts keep unsub-structured due to the interaction between the concrete slab and steel beam.

![Data flow for substructure analysis in ANSYS](image)

2.4 Description of global finite element model

The global finite element model shown in Fig.4 was developed using ANSYS. The elements adopted in this model include SOLID 45 for steel, SOLID 65 for concrete slab and LINK 8 for reinforcement. Bolt pretension action was simulated by PRETS 179 element. The 3D interface elements pair (TARGE170 and CONTA174) was used to model the interaction between column flange and endplate. For validation purposes, the geometrical configuration and material properties of the models are identical to those of the exterior composite joint tested by Vasdravellis (2008). To take into account the Bauschinger effect related to steel when subjected to cyclic loading, multilinear kinematic hardening rule was defined in the material property used. The analysis used the loading procedure suggested by ECCS (European Convention for Constructional Steelwork).
3 Finite element analysis results

To verify the effective modelling the behaviour of the composite joint under cyclic loading, three models have been developed and compared with the experimental investigation reported by Vasdravellis (2008). These models allow for three different conditions of façade beam in the composite joint system, as shown in Fig.6. It can be seen that the composite joint models exhibit behaviour ranging from, what can be considered, the low to moderate moment-rotation capacity when compared with experimental results. The lower capacity was obtained when the façade beam is excluded from the joint configuration. The largest hysteresis loops were obtained for the models that assumed the façade beam to have rigid restraints from the concrete slab and corresponding rigid shear connections to the steel reinforcement. Figure 6 also shows that a better correlation exists between the finite element analytical and experimental results for positive moment (tension at bottom of connection) than that for negative moment. This result reveals the effectiveness of finite element models in simulating the rotation of bare steel joint and compression of the concrete slab on the façade beam and column flange through shear connectors. On the other hand, it seems that finite element analysis underestimates the strength of the joint under negative moment when the rebars are in tension. This can be attributed to the difficulty in accurately capturing the shear transfers between
reinforced concrete slab and deformed façade beam when the joint is subjected to negative bending. However, this result can be regarded to be on the safe side for design work.

The comparison of $M-\theta$ hysteresis curves in Fig.6 shows a close agreement between the results obtained by finite element models with and without sub-structuring. This data was obtained from runs on PC with Intel® Core™2 Duo Processor & 2.32GB RAM using ANSYS Version 11.0 SP1. The average times were 294.97 mins for models that used sub-structuring and 404.51 mins for models that used nonsub-structuring. This saving is expected as the solution of the use pass with fewer degrees of freedom than the time needed to perform the overall analysis of the model.

4 Conclusion

The composite joints under cyclic loading are currently studied using various FE modelling techniques. Nonlinear spring elements and MPC technique have been adopted in this study to model the composite action and façade beam. The adopted model seems to simulate the $M-\theta$ hysteresis curves with reasonable accuracy. It also has been shown that the sub-structuring technique can be used to satisfy the CPU time saving in modelling the composite joint under cyclic loading.

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