Engineering Structures 31 (2009) 1865–1879

Contents lists available at ScienceDirect

Engineering Structures

journal homepage: www.elsevier.com/locate/engstruct

# Modelling beam-to-girder semi-rigid composite connection with angles including the effects of concrete tension stiffness

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ARTICLE INFO

*Article history:*
Received 3 November 2008
Received in revised form
12 February 2009
Accepted 26 March 2009
Available online 24 April 2009

*Keywords:*
Composite semi-rigid connection
Concrete tension stiffness
Beam-to-girder connection
Experimental analysis
Component method

ABSTRACT

The present paper aims to propose a theoretical model for beam-to-girder steel–concrete composite connection. Typical web and seat angles connection was investigated in order to define its moment–rotation behaviour, including the initial stiffness, bending strength and rotational capacity. The proposed theoretical model describes the semi-rigid response of the connection and incorporates the tension stiffening effects of the concrete slab by means of a four parameter power function in which the concrete stiffness and cracking evolution are taken into account.

The comparison between the theoretical model and the experimental results of four cruciform-type tests, including two types of connections, with and without web angles, resulted in accurate validation of the proposed moment vs. rotation model and allowed concluding on the importance of the presence of the web angles, which strongly contribute to the control of the concrete cracking process. In addition, the experimental results confirmed fundamental assumptions of the composite semi-rigid connections, as the effect of the concrete before and after cracking stabilization, the actual contribution of the bolts of the web connection and the shear lag effect in the slab.



## 1. Introduction

Efficacy of steel–concrete composite building construction is strongly dependent on appropriate design of connections. The semi-rigid concept of these connections has been activated in the usual design on the basis of a large number of research activities, which allowed the adoption of practical methods to model this type of structural detail. The component method appears as a powerful tool for designers and has been applied to develop practical modelling of connections in steel construction, useful for both classification of the joints – rigid, flexible or semi-rigid – and identifying its moment–rotation response in order to improve structural analysis. All these efforts have been mainly directed to beam-to-column connections and many research results were already incorporated in practical engineering.

Competition in building construction is the main reason for the studies and developments in the field of semi-rigid connections addressed to steel construction. Choices and decisions concerning connection solutions can be considered as one of the main aspects to be observed in the structural design of steel buildings. The improvement of steel and composite connections for buildings followed the above mentioned reasons and many researches have been conducted during the last decades. The semi-rigid connection concept represents an alternative solution to the traditional concepts: (a) rigid behaviour combined with fully or partially restrained concept or (b) flexible connection. The semi-rigid concept may be taken into account for the definition of structural framing and is addressed to beam-to-column connection, which finally influences the global behaviour of steel building.

The present research was not aimed at analyzing the global frame behaviour of steel buildings. The main goal is to apply the semi-rigid concept either for the case of large steel–concrete floor systems of low buildings or to the components of the floor system of tall buildings which are not part of the bracing system. In general, these large floors are based on large span main girders, combined with a large number of secondary steel beams and steel deck composite slabs. The focus of the present research is the beam-to-girder composite connection model to help design and produce structural efficient semi-continuous composite floor solutions, leading to cost savings.

On the other hand, semi-rigid and partially resistant solutions demand more sophisticated structural analysis, including plasticity and nonlinear behaviour, which is not always available in current design practice. In addition, each type of composite semi-rigid connection should be previously tested in order to obtain

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doi:10.1016/j.engstruct.2009.03.025

**Notations**

| | |
|---|---|
| $A_b$ | Bolt area |
| $A_c$ | Concrete area |
| $A_{c,ef}$ | Effective concrete area |
| $A'_c$ | Equivalent concrete area |
| $A_r$ | Slab reinforcement area |
| $b_{ef,wa}$ | Effective width of a bolt row in the tension zone |
| $BSG$ | Bolt strain gage |
| $c$ | Reinforcement recovering |
| $d$ | Distance from the middle thickness of the seat angle to the beam upper flange |
| $d_{Ac,ef}$ | Distance between the centroid of the effective concrete area $A_{c,ef}$ and the seat angle |
| $d_b$ | Bolt diameter |
| $d_{conc}$ | Concrete flange thickness, excluding any ribs |
| $d_p$ | Distance from the middle thickness of the seat angle to the first bolt row |
| $d_{M16}$ | Bolt diameter of reference |
| DT | Displacement transducer |
| $d_{wa}$ | Distance from the horizontal web angle corner to adjacent bolt row |
| $d_1$ | Distance from the middle thickness of the seat angle to the web angles |
| $e_b$ | Distance between the bolt row and the edge of the plate in the direction of load transfer |
| $e_{co}$ | Distance from the edge of the flange of the girder to the first shear connector |
| $e_{wa}$ | Distance from the vertical web angle edge to the bolts |
| $E$ | Elastic modulus of steel |
| $E_c$ | Elastic modulus of concrete |
| $E_r$ | Elastic modulus of the reinforcing steel |
| $F_c$ | Force at the centre line of the horizontal flange of the seat–web angle |
| $F_p$ | Tensile force at the first row of bolts |
| $F_r$ | Resultant tensile force at the reinforcing steel bars |
| $F_{cr}$ | Force which provoke cracking within the effective concrete area $A_{c,ef}$ |
| $f_{ctm}$ | Mean tensile strength of concrete |
| $f_u$ | Tensile strength of steel |
| $f_{ub}$ | Tensile strength of steel of the bolt |
| $f_{up}$ | Tensile strength of steel of the plate considered |
| $f_y$ | Yielding strength of steel |
| $f_{y,r}$ | Yielding strength of the reinforcing steel |
| $h_c$ | Distance from the middle thickness of the seat angle to the steel connection rotation centre |
| $h_t$ | Distance from the equivalent spring of the bolts in the tension zone to the steel connection rotation centre |
| $k_b$ | Stiffness of the bolts in tension |
| $k_{bs}$ | Stiffness of the bolts in shear |
| $k_{bwb}$ | Stiffness of the beam web in bearing |
| $k_c$, $k_{ef,c}$ | Equivalent stiffness of the seat angle bolt row |
| $k_{cns}$ | Coefficient introduced to take into account a non-uniform stress distribution in the tension member |
| $k_{conc}$ | Stiffness of the reinforced concrete in tension |
| $k_{ef,i}$ | Equivalent stiffness of a bolt row in the tension zone |
| $k_p$ | Stiffness of the first row of bolts of the web angle |
| $k_r$ | Stiffness of the reinforcement in tension |
| $k_s$ | Stiffness of the shear connectors |
| $k_{sab}$ | Stiffness of the seat angle in bearing |
| $k_t$ | Equivalent stiffness of the bolt rows in the tension zone |
| $k_{wa}$ | Stiffness of the web angles in bending |
| $k_{wab}$ | Stiffness of the web angles in bearing |
| $k_\theta$ | Initial rotation stiffness |
| $k_{\theta,comp}$ | Initial stiffness of the composite connection without concrete contribution |
| $k'_{\theta,comp}$ | Initial stiffness of the composite connection considering tension stiffening effects |
| $k_{\theta,p}$ | Hardening stiffness |
| $k_{\theta,steel}$ | Initial stiffness of the steel connection |
| $L_a$ | Breadth of the flange of the girder |
| $L_b$ | Bolt length |
| $l_{sl}$ | Breadth of the slab |
| $l_t$ | Length over which slip between steel rebar and concrete occurs |
| $L_{wa}$ | Length of the web angles |
| $M$ | Bending moment |
| $M_{cr}$ | Bending moment at stabilized cracking pattern |
| $M_{J,Rd}$ | Bending strength according to Eurocode 3 |
| $M_u$ | Ultimate bending moment |
| $M_{u,comp}$ | Ultimate bending moment of the composite connection |
| $M_{u,steel}$ | Ultimate bending moment of the steel connection |
| $m_{\max}$ | Distance between web angles yield lines at the upper edge of the web angles |
| $m_y$ | Distance between web angles yield lines |
| $M_0$ | Reference bending moment |
| $n$ | Shape factor |
| $N_s$ | Minimum value between the number of connectors in the hogging region and the number needed to fully interaction |
| $p_b$ | Pitch of the seat angle bolts in the direction of load transfer |
| $p_{wa}$ | Pitch of the web angle bolts |
| $RSG$ | Rosette strain gage |
| $SG$ | Strain gage |
| $t_p$ | Thickness of plate |
| $t_{wa}$ | Thickness of web angle |
| $V_{wa}$ | Resultant shear force in the web angles |
| $y_{conc}$ | Distance between the centroid of the uncracked reinforced concrete flange and the top of the steel section |
| $y_g$ | Position of the resultant shear force |
| $y_r$ | Distance from the reinforcement to beam upper flange |
| $z_i$ | Distance from the middle thickness of the seat angle to a bolt row |
| $z_t$ | Loading arm |
| $z_0$ | Distance between the centroids of the uncracked unreinforced sections of the concrete flange and the composite beam |
| $\alpha_m$ | Modular ratio: $E_r/E_c$ |
| $\Delta_{u,r}$ | Ultimate elongation of the longitudinal slab reinforcement |
| $\Delta_{u,s}$ | Deformation capacity of the shear connectors |
| $\Delta_{u,sa}$ | Ultimate deformation of the seat angle |
| $\varepsilon_s$ | Strain in the reinforcing bar |
| $\varepsilon_{s,mu}$ | Ultimate average strain of the reinforcement |
| $\varepsilon_{sy}$ | Strain at yield stress of the reinforcing bar |
| $\phi$ | Average rebar diameter |
| $\rho_s$ | Reinforcement ratio: $A_r/A_c$ |
| $\rho_{s,ef}$ | Reinforcement effective ratio: $A_r/A_{c,ef}$ |
| $\theta$ | Rotation |
| $\theta_u$ | Rotation capacity |
| $\tau_{sm}$ | Average bond stress along the introducing length $l_t$ |
| 1ws | Connection of group 1 with web and seat angles |
| 1s | Connection of group 1 with seat angle only |
| 2ws | Connection of group 2 with web and seat angles |
| 2s | Connection of group 2 with seat angle only |