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The Use of Composite Connections in Practice

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Summary

For any new design approach to be adopted by practising engineers, genuine benefits must be attainable without a disproportionate increase in design effort. Making use of semi-continuity between the members of a frame offers the potential for significant benefits. A design guide is currently being developed which demonstrates how these benefits can be realised in braced composite frames. The manual provides both frame and connection design procedures, and includes tabulated information to reduce design effort.

1 Introduction

Semi-continuity between frame members can be used to reduce the overall cost of a steel or composite frame. Beams can be shallower or lighter than in "simple construction", and connections require considerably less fabrication effort than those in continuous frames. Connection performance has a major influence on frame behaviour.

It is essential that in developing frame analysis and design methods, consideration is given to both simplicity and the connection characteristics that are required in order to use the method. The three principal connection characteristics are rigidity, strength and ductility (or rotation capacity). Plastic analysis at the ultimate limit state (ULS) benefits from being simple. Its use requires the connection strength (moment resistance) to be predictable with reasonable accuracy. Connection ductility is also essential. Models exist for calculating strength, whilst adequate ductility can be proven by testing when standard details are used, or by using appropriate detailing rules. In contrast, elastic analysis relies on an ability to quantify connection rigidity. Current methods are labourious, and do not allow this quantification with sufficient accuracy for ULS calculations. However, more approximate predictions of rigidity are acceptable for calculating frame performance at the serviceability limit state (SLS).

A *Composite Connections Manual* is currently being produced by the Steel Construction Institute (in conjunction with academics, consulting engineers and fabricators), that considers both composite connection and braced frame design. The composite connections are based on standard details which achieve continuity through both the steel connection itself, and the tensile reinforcement in the slab. This paper presents some of the principal sections in the manual.

2 Standard Connection Manuals

The SCI/BCSA Connections Group was established to develop industry standards for structural steelwork connections in the UK. The benefits of standard connections include;

- connection characteristics can be accurately determined by testing or semi-empirical methods calibrated against tests on similar details,
- reduced disagreements between designers (frame members are traditionally designed by a consulting engineer, and connections by a fabricator),
- the development of software is encouraged (using agreed procedures),
- standard connection capacities can be tabulated to reduce design effort,
- a manufacturing approach to connections is promoted (using rationalised components),
- reduced uncertainty at the tendering stage,
- reduced errors (when bolt sizes and grades are rationalised),
- avoidance of expensive, difficult to erect connection details.

The group have already produced three manuals dealing with steelwork connections. These will be complemented by the current work on a manual for composite connections.

3 Composite Connections Manual

3.1 Potential Benefits

Any new design method which involves even minor changes to existing practice will only be adopted if genuine and significant benefits can be demonstrated.

A study undertaken by the SCI has shown that it is possible to reduce the depth or weight of an individual beam by up to 25%. Depth savings may be particularly important, allowing easier integration of services, reduced cladding costs etc. However, to achieve genuine benefits, savings must be possible for a substantial number of the beams in a given frame. For example, if the designer is aiming for depth savings, these may need to apply to all the beams in a floor if cladding costs are to be reduced. Depth savings in certain zones may be sufficient to facilitate service integration. The choice of frame layout has a major influence on the overall benefits that can be achieved, as explained below.

3.2 Frame Layout

The size of a beam in a composite frame is generally governed by one of two conditions;

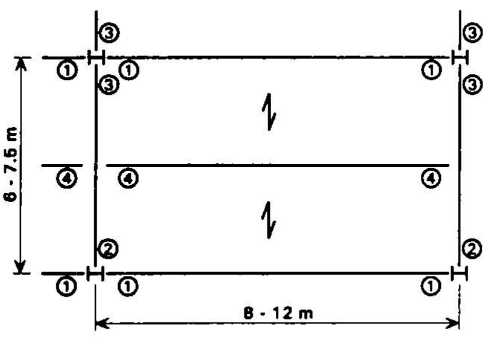
- the moment resistance of the composite beam at the ULS,
- the total deflection of the beam at the SLS, the greater part of this deflection being due to the weight of the slab applied to the steel beam during (unpropped) construction.

Table 1, taken from the manual, indicates which condition governs for a range of loading types and steel grades. The table is applicable for spans up to 12m. A question mark (?) indicates that either condition might govern. The beam span to depth ratio is also a useful indicator of the relative importance of ULS and SLS conditions. Limits are suggested in the manual for different scenarios. If the benefits of using semi-continuity are to be realised, connections to beams which are governed by composite moment resistance at the ULS should be detailed to provide strength. Connections to beams which are governed by SLS deflections should be detailed to provide rigidity. Rigidity in the bare steel state is essential to reduce the construction stage component of the total deflection. Certain other recommendations should also be considered when choosing the frame layout:

Loading	Steel Grade	Critical Condition	
		SLS	ULS
Distributed	S355	x	
	S275	?	?
Central point	S355		x
	S275		x
Points at third span	S355	?	?
	S275		x
Multiple points	S355	x	
	S275	?	?

Table 1: Conditions which govern beam design

- Orthogonal connections to a column should not both be composite. This restriction is imposed to prevent over congestion of reinforcement.
- Connections to perimeter columns should not rely on composite action, since anchorage of reinforcement is difficult to achieve at the slab edge. Connections to perimeter columns are therefore relatively weak, and excessive unbalanced moments are not introduced into the columns. When moments are large, local strengthening, or an increase in column section size, may be necessary.



Connection Type	Principal Characteristics
1	Rigid, Steel
2	Pinned, Steel
3	Strong, Composite
4	Pinned, Steel

Figure 1: Typical floor beam layout to achieve beams of similar depth

Possible framing arrangements which capitalise on these principles, and corresponding connection details, are suggested in the manual. One possible framing arrangement is reproduced in Figure 1. Note that for maximum benefit the connection Type 4 in Figure 1 would need to be rigid in the bare steel state. Unfortunately, rigidity is difficult to achieve for a beam to beam steel connection, making the use of a nominally pinned connection unavoidable in most such situations.

3.3 Frame Design

3.3.1. Plastic hinge analysis at ULS

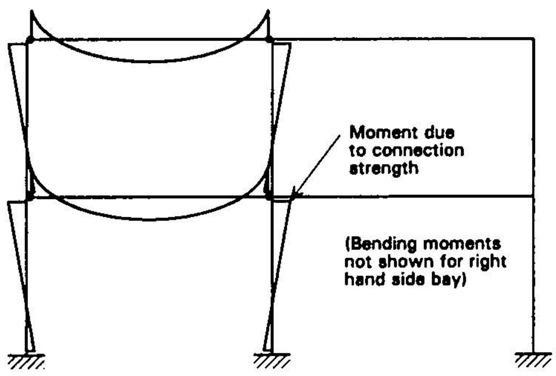


Figure 2: Moment distribution at the ULS

Beam design is based on the assumption that plastic hinges form in the connections. The resulting negative (hogging) moments at the beam ends allow the required beam plastic moment resistance to be reduced. This is shown schematically in Figure 2. The assumption that plastic hinges form is only valid when the connections possess sufficient ductility, which has been shown by testing for the standard details.

Internal columns are designed for axial load only, caused by imposed load applied to all the beams. Pattern loading cases with reduced axial load combined with moment applied to the column have been shown to be less critical by testing and finite element analyses [CIMsteel *Semi-continuous braced frames*]. This means that column design is no more complicated than that for columns in "simple" frames according to BS 5950. Perimeter columns are designed for axial load combined with an unbalanced moment equal to the connection capacity.

3.3.2. Elastic analysis at SLS

Connection rigidity reduces beam deflections significantly. By using standard connection details, rigidity can be quantified with acceptable accuracy for deflection calculations, based on test results.

The SLS procedures given in the manual build on previous work by the first author [CIMsteel *Semi-continuous braced frames*], providing simple formulae to conservatively calculate deflections. For example, the deflection of an internal beam subject to distributed loading is given by $\delta = 3/384\ (wl^4 / EI)$. (This equation is based on the rigidity of the standard connections, and may be subject to minor adjustment as development work on the manual progresses.) Formulae are given for various load arrangements and end conditions. For less common situations, or when more accuracy is needed to reduce calculated values, a full procedure taking into account specific member and connection rigidities is given in an appendix.

3.4 Outline Procedure for Beam to Internal Column Connections

One of the standard connection types featured in the manual is a composite connection framing into the column flange. Such a connection could be used to reduce the moment resistance required from a beam at the ULS, and offers reasonable rigidity in both the bare steel and composite states.

The outline procedure for calculating connection moment and shear resistances is described in the manual. Components which have a significant influence are the;

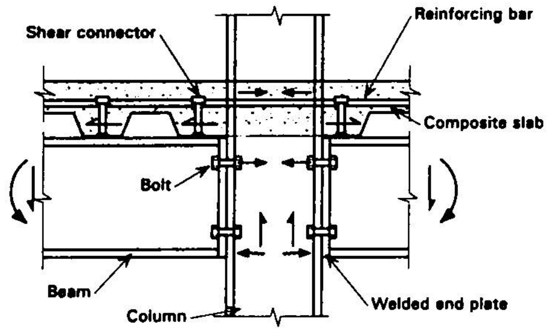


Figure 3: Connection components

- tensile resistance of the reinforcement,
- tensile resistance of the upper bolts,
- compression resistance of the beam lower flange,
- compression resistance of the column (considering buckling and bearing),
- longitudinal shear transfer between the beam and slab,
- shear capacity of the bolts.

These are shown in Figure 3.

In addition to resistance, sufficient ductility is essential if the frame design procedures described in the manual (see Section 3.3) are to be adopted. Detailing rules to ensure ductility are described in the manual, and the standard connections have been shown by testing to be satisfactory. A minimum percentage reinforcement (1% of the slab cross-sectional area) is necessary to give sufficient ductility.

3.5 Step-by-Step Connection Design Procedure

Step-by-step design procedures for the principal connection types are given in the manual, and are illustrated by worked examples. These procedures could be used to design a connection by hand, but are more likely to be used to write software. As with previous connection manuals, a software producer is included in the task group responsible for draughting. The benefits of this relationship include;

- the logic of procedures is verified as they are translated into coding and tested,
- commercial software to simplify the connection design process will be available upon publication of the manual.

3.6 Design Tables

Two types of table are included in the manual; tables which give moment and shear resistance for a range of standard connections, and tables which give the physical details of these connections.

The resistance tables will simplify the work of designers by eliminating extensive calculations when standard details are adopted. In choosing a standard detail, the designer will also be assured that the connection;

- is ductile (has sufficient rotation capacity),
- has sufficient rigidity,
- can be fabricated economically (since it is based on fabricators' recommendations).

An extract from a typical table showing the moment resistance of a range of composite "major axis" connections is given in Table 2. Moment resistance is expressed as a function of the composite beam resistance in sagging. It can be seen that the connection moment resistance increases as reinforcement is added. However, the tensile force in the bars must be balanced by compression in the column, and if an excessive amount of reinforcement is added the column will require local strengthening. Supplementary tables in the manual therefore indicate the maximum percentage of reinforcement which can be used with different column sizes before local strengthening is required.

Steel Beam Section	Percentage of slab reinforcement				
	0.5%	1.0%	1.5%	2.0%	2.5%
533x210x122	0.09	0.19	0.28	0.38	0.47
533x210x109	0.10	0.21	0.31	0.41	0.52
533x210x101	0.11	0.22	0.33	0.44	0.55

Table 2: Connection moment resistance expressed as a proportion of the composite beam positive (sagging) moment resistance, for S355 beams.

Considering the physical details of the connections, it was decided from the outset that only one solution would be given to a particular problem. One of the reasons for this approach is to avoid complications when the frame members and connections are designed by different parties. It was felt that if alternative (e.g. cleated, fin plate or end plate) details were provided there would always be cases when a consultant specified one type of detail, and the fabricator wished to use another. Because frame behaviour is inextricably linked to connection behaviour this would necessitate a review of the member design. If only one option is available there can be no arguments! Perhaps a more legitimate reason is that steel end plate details are the most suitable for use in composite connections, because they provide a direct load path for compression from the beam bottom flange to the column, and have sufficient rigidity to facilitate erection.

The over-riding philosophy for connection detailing is one of avoiding complexity; local column strengthening is avoided if possible, to keep fabrication and therefore costs down to a minimum. If a chosen detail requires local strengthening, this can be avoided either by choosing an alternative detail or by increasing the column section size.

4 Conclusions

Two criteria must be satisfied for any new idea to be adopted by practising engineers;

- genuine benefits are achievable,
- design methods are simple, and appropriate aids (tables and software) are available.

The manual currently being produced demonstrates how the benefits of semi-continuous composite frames can be realised, and presents details and procedures which are based on the knowledge and experience of a broad cross section of practitioners. It includes design tables which simplify the work of both the frame designer and the fabricator. Software is being developed in parallel with the manual.