CROSS Safety Report

Connection fixity considerations for steel frame modelling

This month we present a CROSS report concerning the modelling of joints when using computer programs. Applying rotational releases to joints in models but subsequently designing the connections as rigid leaves a fundamental mismatch between analysis and design which may lead to unsafe structural connections, argues a reporter.

Report

This report concerns the modelling of joints when using computer programs. In some cases, says a reporter, engineers are applying rotational releases to joints in models but subsequently designing the connections as rigid. This leaves a fundamental mismatch between analysis and design which may lead to unsafe structural connections.

The reporter cites three cases where they have regularly seen this being done:

- Instead of applying a 0/10/20% partial fixity to the bases of portal columns, with 0% fixity used at the ultimate limit state, the model is created with a single partial-fixity definition which is applied globally, so acting at the ultimate limit state.
- For simply supported beams, a partial fixity is applied which helps reduce the mid-span sagging moment and mid-span deflection.
- In models where the end releases are leading to instability, a partial fixity is applied to provide some degree of continuity in the structure to allow the analysis to proceed.

In all cases, the model is applying a rotational spring to some or all joints in the model, with the analysis then being carried out on the basis of semi-rigid joints. The design for the connections is then completed through the design software which is written in line with the SCI Green Books. However, because the design software detects an end moment in the beam or column, it will not permit the connection to be designed as a simple non-moment connection, but applies a moment-resisting connection as per the SCI Green Book P398. The reporter goes on to say that the software user has therefore designed the structure with rigid joints whereas the analysis was undertaken on the basis of semi-rigid joints.

A semi-rigid connection requires the joint to have some ductility and so be able to rotate. This happens because of the flexibility of the end plate. This is not the case in a rigid connection where the end plate is taken to be thick and so does not yield. Therefore, from a rotational stiffness point of view, the end plate is not designed to allow the rotation that would be required to match the analysis model. The connection is significantly stiffer than that modelled. This means there is a significant danger that the connection will attract a much higher force than it is designed for. This could lead to yielding in components of the connection that were not designed to accommodate the higher forces, such as the bolts or flanges, but could also in some circumstances lead to premature failure of the joint.

The cause of the problem, continues the reporter, is two-fold.

1) A fundamental misunderstanding of connection design and the underlying component model used in the SCI Green Book for moment connections coupled with a lack of understanding of the implication of applying partial fixities/rotational springs in frame models.
2) A lack of understanding of the purpose of the common approach to partial fixities in portal frames of applying 0/10/20% fixities or not understanding how to do this in the software and instead applying global partial fixities without understanding the consequences.

The basis of rigid connections is stated in the SCI Green Book P398.

Key learning outcomes

For civil and structural design engineers:

- Designers should understand the engineering principles and design rules that underpin specific modelling software before use
- Ensure the model correctly and appropriately represents the structure under analysis
- Ensure the structure that is being designed is compatible with that modelled
- The SCI Green Books provide a basis for connection design that should be sufficient in most cases
- Designers should specify practical connection details that match their modelling assumptions and at least overview fabrication drawings to ensure their design intent is realised
- Ensure that there is a suitably qualified and experienced engineer with overall responsibility for design and checking

But some engineers may be designing connections using software without having read and understood the guidance. The reporter contends that there has been long-standing practice whereby the consulting engineer designs the elements, and the connections are designed by others. This has led to a situation where many consulting engineers have had little exposure to connection design and so lack a good understanding of how connections impact modelling. There is also a lack of understanding of how rigid and semi-rigid connections differ fundamentally in their behaviour. As semi-rigid connections are likely to become more common, in the opinion of the reporter, there is a need for more design guidance.

Expert Panel Comments

This report highlights profound issues that have troubled researchers and code writers since the 1930s. The reality is that all steel connections are semi-rigid and it is not really possible to define their spring stiffness with any confidence even if the full details are known. Experiments show quite significant variations even between notionally identical connections. Moreover, the moment rotation characteristic is usually non-linear. It is not possible for a connection designer to offer a particular semi-rigid performance nor is it generally possible to provide a connection not exceeding the strength defined by the main designer (one of the reporter's concerns).

It was these observations that originally led to the concept of ultimate load design. A structure's stress distributions under lower loads might differ substantially from elastic predictions (not least because of connection variability) but provided the performance of the connections are compliant with ultimate load conditions, the structure should have adequate strength.

In terms of modelling, two conditions can be defined: modelling for strength and modelling for deformations. For the latter, connections will normally exhibit some rigidity, especially under low (service) load conditions and this can be accounted for in the modelling. Moreover, it should be accounted for otherwise some deformations might be underestimated (such as horizontal column bow if 'pinned ended' beam connections actually transmit moments to columns).

For an ultimate load model, it is best if connections are modelled 'pin ended' or 'fixed' since long practice has shown such assumptions generally result in safe designs. But no connection is actually a pure pin and no connection is ever fully rigid. What is essential in the detailing stage is that pin-ended connections exhibit the requisite ductility commensurate with the rotations required of them at ultimate load. Green Book compliance will normally assure this.

The reporter has expressed some concern that modelling assumptions varying from reality may 'overstress connection components'. This may well happen at low loads with notionally pin-ended connections, but is not of concern since the imposed deformations (even with permanent yielding) are strain controlled and will not cause structural failure. A shear-only (pin) connection has to be capable of deforming, elastically or inelastically 'out of plane' but still carry shear 'in plane' and that is why proper detailing to accommodate the movements is so essential.

Caution is required when unusual structures are being designed. Extra long length beams will normally have to carry appreciable end shears necessitating connections with many bolt rows. If these are designated 'pin ended' it may become problematic to assure they can be detailed to exhibit sufficient ductility. In end plate connections, ductility requires that bolt columns are widely spaced to allow the end plate to deform. Thus, there is an impact back on the main designer to assure the provision of members that are wide enough to accommodate such spacings. SCOSS (now CROSS) issued a Safety Alert in 2018 concerning the *Effects of scale* – this included consideration of connections for long-span steel beams.

The reporter expresses concern about the interface between main designers and connection designers, whereby main designers have little experience of connection design. That concern is justified. A key obligation of main designers is to size and configure frames such that the connection design they require is feasible, and that cannot be done without experience.

It is interesting to question why pinned releases on the model are causing instability. The author does not state what that instability is or where it is coming from. One cause may be related to torsional instability in the beams due to torsional releases being applied along with major and minor axis releases. While Green Book connections do not normally have an explicit torsional capacity, they do offer torsional restraint and thus it is valid to not release the beams about this moment axis. This is conditional on the engineer then checking for any torsion that is reported in the analysis and designing for it appropriately (or designing it out).

Another cause may be that the frame actually requires diaphragm action from the floors to maintain stability. Mimicking diaphragm action by applying minor-axis moment connections is dangerous as it analyses the structure in a way that is not aligned with how the structure is intended to behave. In addition, designing and detailing connections for non-existent minor axis moments is an unnecessary cost.

The reporter raises very well the point that engineers must understand the engineering principles and design rules which are written into and underpin the software they are using. Equally those checking designs must also appreciate the same.

There should be compatibility between analysis and design; otherwise, it is likely that some of the structure could be under-designed. It is essential that all design assumptions are verified. Designers using specialist software need to be properly trained, experienced and competent to be able to rely on the results. It is also essential that analysis and design are both checked. Checking using alternative methods may more readily highlight errors. The report also raises the point that there should be an engineer with overall design oversight/ coordination responsibility, as otherwise work packages (in this case member design and connection design) may not be compatible with one another.

A report, *Modelling of structures*, published by CROSS-AUS in August 2022 considers the limitations and basis of modelling, and also examines the verification of modelling.

The full report, including links to guidance mentioned, is available on the CROSS website (report ID: 1139) at **www.cross-safety.org/uk/safety-information/cross-safety-report/connection-fixity-considerations-steel-frame-1139.**