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NZ Heavy Engineering Research Association

HERA Notice: What You Must Know if Considering Importing Seismic Resisting Fabricated Steel Structures

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Background

The design and construction requirements for structural steel buildings in New Zealand have been developed to ensure reliable performance in a cost-effective manner. They comprise of a carefully tuned suite of seismic resisting systems whose performance demonstrated its pedigree during and following the 2012 Canterbury earthquakes. The use of steel as a reliable material for bracing systems was validated by its exceptional performance and resulting low damage states, most of which exceeded design engineers' expectations when compared to the scale and intensity of the seismic events experienced. The systems behaviours demonstrated ease of achieving the life safety aspects of the NZ Building Code leading to confidence in the material and design procedure's developed by the Heavy Engineering Research Association (HERA) and industry partners. So it is not surprising that many buildings in the Christchurch rebuild effort are expected to be built in structural steel to New Zealand specifications.

Figure 1: The 12 story HSBC Tower is an example of the better than expected performance of seismic structural steel structures in Christchurch. The insert shows the inelastic demand on the Eccentrically Braced Frame steel frame.

HERA, as the New Zealand steel construction industry research organisation, has been intimately involved in the development of the New Zealand design and fabrication framework. Furthermore, HERA's other roles includes education and advice to the local industry and ongoing enhancement of the industry's focus and competitive use of steel. HERA and Steel Construction New Zealand (SCNZ)

are also regularly involved in compliance issues related to local and imported fabrication and frequently provide advice on both the strengthening of existing buildings using steel and the development of new low-damage solutions that are expected to focus damage into easily replaceable /recoverable components leaving the main part of the structure generally unaffected.

This HERA notice aims to identify the key issues that must be addressed in order to reliably design and document steelwork compliance with imported fabricated steel and to assist designers, owners and others to ensure its compliance within the current New Zealand regulatory framework.

NZ Steel Construction Standards and Material Selection – A Carefully Tuned Framework

The NZ performance-based building regulations for steel construction are centred on the Steel Structures Standard NZS 3404. NZS 3404 is underpinned by a series of material, welding and related standards and key design documents. In respect to materials and their fabrication, the current key document is NZS 3404: Part 1:2009 which lists a range of mechanical properties and standards that steels for seismic frames must meet and comply with.

For example, steel sections for NZ seismic frames need to meet specified yield/tensile strength ratios, elongation values, ratios of maximum actual to specified strength, and fracture toughness requirements. Most seismic resisting systems are designed to undergo controlled damage in a severe earthquake, even parts or components within low-damage systems. Any elements of steel framed systems which are used in ductile or energy dissipating systems are required to meet most stringent material property requirements. These requirements are categorised in the corresponding AS/NZ standards as seismic (S0) grades.

For the acceptance of steels to NZS 3404, the supplier has to provide evidence of compliance with relevant material supply standards based on test certificates provided by an accredited laboratory. The independent testing lab must be accredited by signatories to the International Laboratory Accreditation Corporation (ILAC) Mutual Recognition Agreement. In addition, the paperwork must be genuine and traceable to the steel being purchased. When dealing with the NZ steel supply chain, this system has been applied with integrity and so the paperwork from these organisations has been trusted.

However, as steel is now being sourced from a wider range of suppliers, and the conformity assessment of products is a specialised skill; third-party conformity assessment is becoming the normal approach internationally. For example, the Australasian Certification Authority for Structural Steels (ACRS) offers this service for products made to AS/NZS steel Standards and certifies over 150 manufacturing locations, in 15 countries around the world.

Globally, only four steel mills currently manufacture to this standard, with the bulk of the sections being of Australian origin and the plate of New Zealand origin. Two of the three principal suppliers of hot-rolled structural sections to New Zealand, Onesteel (Australia) and Tung Ho (Taiwan)), are already third party certified for their full range of sections manufactured to AS/NZS 3679.1. The third supplier, Siam Yamato Steel (SYS, Thailand), is in the process of applying for ACRS certification. For seismic members, NZS 3404 states that steels shall conform to the range of approved standards.

However, the standard allows a pathway for non-conforming or so-called 'unidentified steels' through approval granted by a qualified metallurgist or materials engineer who can verify that the steel materials produced to internationally recognised standards are equivalent. Demonstrating equivalence is not always straightforward, as the material supply and suite of testing standards used worldwide are often not equivalent. It requires considerable experience and effort to be able to conclusively demonstrate equivalence of steels for use within or as seismic members.

NZ Steel Framing Seismic Design Philosophy – Proven to Perform

There is a comprehensive range of literature, e.g. available from HERA, which describes NZ seismic design philosophy and its importance to deliver safe buildings. A good introduction to this topic is the Report to the Royal Commission of Inquiry into the Building Failures Caused by the Christchurch Earthquakes[1]. Former HERA Structural Engineer Charles Clifton is a co-author of this report and one of the principal authors of the steel construction part of the report.

Buildings are designed to undergo controlled damage in a severe earthquake. This damage is concentrated into elements of the seismic resisting system that can dependably deform during the earthquake, whilst the rest of the seismic resisting system is protected from other than, at worst, minor damage.

Connections between elements must be capable of accommodating the expected deformation without failure. The damage resisting elements are called 'primary elements' and the damage protected elements are called 'secondary elements'. For all seismic resisting systems to work as intended there is a carefully developed and validated design procedure to ensure that this occurs. This is called the 'Capacity Design Procedure'. The exact details are seismic resisting system specific. While the concept is simple, applying it in a cost-effective manner is not. In the case of the NZ capacity design procedures, the fundamental concepts of these date back to a 1990 PhD project by Greg MacRae (now Associate Professor at the University of Canterbury). The concepts have been slightly modified through further research since then and represent a balance of dependability and cost-effectiveness.

This balance is difficult to get right and involves considerable expert judgement in setting the detailed provisions. Similar research has gone into design and detailing of the rest of the structural system that is tied into the seismic resisting system and supports the vertical loading on the building. To achieve this, those involved need to

1) carefully balance the mechanical properties of the steels (such as the yield and tensile strength of the steel sections to be joined);
2) use suitable weld joint designs;
3) match the strength and ductility requirements of the welding consumables to the steels joined and
4) fabricate by strictly adhering to allowable imperfection limits.

HERA, in its extensive research programme comprising >20 years of experimental testing and numerical modelling (e.g. NZWC Report R8-28 Earthquake Performance of Welded Moment Resisting Connection),has demonstrated that, for typically used steels of largely Australasian origin, the NZ design procedures perform as expected. However, the research also demonstrated that, when operating outside these procedures (e.g. using too strong a steel or welding consumables, exceeding allowable weld imperfection limits or lack of toughness), fracture of the connection or the primary elements is more likely. This potentially leads to catastrophic failure of a connection (e.g. Figure 2).

[1] http://canterbury.royalcommission.govt.nz/documents-by-key/20110923.14/$file/ENG.ACA.0016.pdf.

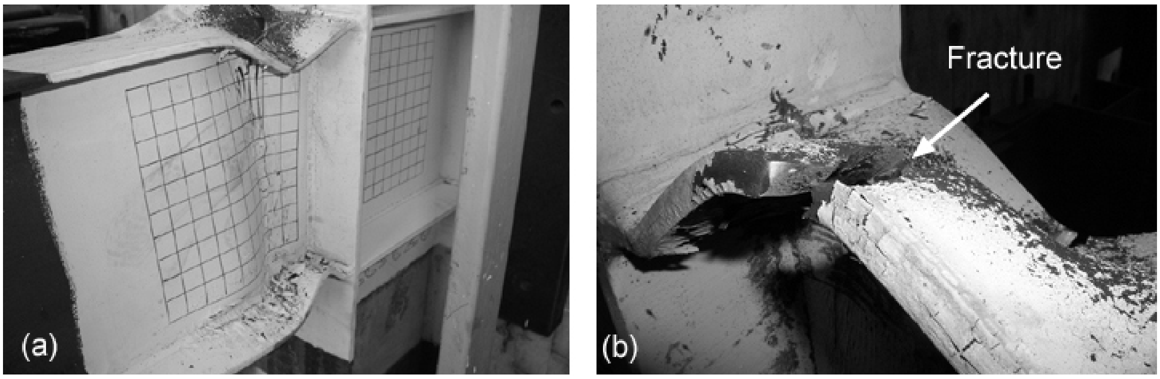

Figure 2. Photos of one of the seismic forces simulation tests performed as part of the HERA seismic research program. The plastic deformation has developed in the horizontal beam(a) and failure is demonstrated as intended in the plastic hinge following applied loads well over the design limit (b).

The 2010/2011 Canterbury earthquakes confirmed the HERA research findings. Some examples of poor detailing were observed, leading to fractures, but these were limited. Despite the peak intensity of these earthquakes being well above design level, the excellent performance of complying design and detailed systems prevented unexpected failures from occurring. The need to use the latest standards was clearly demonstrated in one case, where fracture occurred in a steel member that met the design standards of the day, but didn't achieve the current requirements for the mechanical properties. Notwithstanding this, damage to the steel systems was limited, readily repairable and also showed the inherent strength reserves of a well-designed and detailed steel framed system.

Equivalence Evaluation is Technically Difficult

To demonstrate the complexity of the assignment to prove equivalent of steels in this framework, the following illustrates some of the points where equivalence of steel grades needs to be proven.

- **Controlled yielding and development of plastic hinge**
  Imagine a typical seismic moment connection consisting of an I-section beam welded to an I-section column. At a design level earthquake, controlled yielding (damage) is to occur within the beam section outside the welded regions developing what is called the plastic hinge. For this to dependently happen, we have to restrict yield strength to a minimum starting value above which yielding will occur. We also have to limit its 'overstrength' i.e. the maximum yield strength that is possible by considering the range of yield strengths from a single mill. This is important because if this yield value is too high, the beam does not plastically deform at the intended load and it will develop excessive forces on the ideally strength matched weld and may produce unwanted weld failure. So to ensure robustness of the existing NZ design procedures, seismic steel grades complying with NZS 3404 need to have a yield strength sitting between the nominal value f_y and a maximum of 1.33 f_y

- The nominal yield strength used in design is guaranteed by the product standard, such that the actual measured strengths are always higher than this value, which can sometimes result in the temptation to 're-grade' the material. This is unsafe as this has already been accounted for in the derivation of the capacity factors used in design. For mills with good factory production control systems, the statistical variation of the yield strengths is kept low to ensure that the spread of values is as narrow as possible.

  It is HERA's experience that specifically guarding the 'overstrength'- element is critical. Therefore we have the introduction of 'seismic' grade steel as it is always easy to argue with the unaware client that the steel is stronger than required which clearly is the wrong approach if we require

controlled yielding in a connection. In global markets this concept may be foreign to some steelmakers, and this upper limit on strength is a new concept that they may have difficulty achieving.

Figure 3: Maintaining traceability of structural long and plate product to mill certificates is essential to demonstrate material conformance

Additionally, in order to achieve the required amount of yielding of a connection before it fails (e.g. through overloading), the ratio of the tensile strength to the yield strength, together with the elongation after fracture both need to meet specified minimum values. The ratio of tensile to yield strength must be sufficiently high to spread yield over sufficient length of beam to avoid local necking and fracture, while sufficiently low to avoid excessive strength gain in the plastically deforming beam. This becomes even more important for the active links of eccentrically braced frames, where the inelastic demand is higher.

Furthermore, for particularly heavier sections, in order to avoid the development of fracture pathways that are brittle and may cause sudden failure with potential collapse, minimum fracture toughness requirements need to be achieved. Fracture toughness is typically indicated via the Charpy V-Notch Toughness Value at the specified minimum operation temperature. For AS/NZS steels made in Australia and New Zealand that do not have an impact designation, the brittle fracture provisions given in NZS 3404 already presume a minimum toughness.

While the above described mechanical properties of steel need controlling, the material size tolerances of the plates or sections used also need to be carefully controlled. Imagine a specified steel section is out of tolerance (e.g. “too big”). Whilst being too big in a standard static design is not a problem, in a seismic frame it can be a significant problem because oversize members act like ‘overstrength’ steel and, by resisting yielding in the desirable hinge location, put a higher load on the welds that may fail despite being perfect.

Equally important are too small or under-dimensioned steel sections that may yield prematurely, especially if in the lower yield strength band, reducing the resistance of the building to stay damage free and in the elastic range. NOTE: AS/NZS steel I-sections have much tighter controls on their cross sectional area compared to those supplied from elsewhere through a mass tolerance of ±2.5%.

To address these design issues for different sections and steels, NZS 3404 uses capacity factors. These capacity factors consider the variation between the actual and nominal geometries, inaccuracies in the design equations and the variability of the yield strength of the steel (taken to have a coefficient of variation of 10% in NZS 3404 from tests on materials sourced from a single mill).

It is important to understand that 'unidentified' steel may not have the same distribution of mechanical properties as those steels which do comply. Hence, they, cannot be used in seismic resisting systems without the same extent of testing to establish material properties that would have been undertaken for complying steel. When this is done, the steel is reclassified from "unidentified" to the appropriate steel type. It is important that this is done to material test standards recognised by NZS 3404 and by a laboratory that is accredited by an ILAC signatory to do these tests.

Equally, it needs to be understood that the design of bolted and welded connections according to NZS 3404 is based on design expressions and capacity factors that are directly related to relevant sections of the referenced standards for bolted and for welded connections. For these connections, proof of performance has also been established based on statistical analysis of test results obtained from complying bolt material and welding consumables used with complying steels.

In practice, in order to prove equivalence this means that, via specific testing for each batch of 'unidentified' steel, the steel's mechanical and dimensional properties need to be confirmed to be in line with NZS 3404: Table 3 – Category 1 and 2 seismic member material requirements

- **Steel Grade Class Strength Limitation**

  The NZ 3404 steel construction design framework limits the usable steel grade class to a maximum yield strength of 360MPa. This is to ensure that the required ductility and fracture toughness is available, combined with ease of welding, including availability of a matching consumable range. In general, higher strength steels have higher carbon equivalents and as the result of greater hardenability require more care during welded fabrication to ensure yield and toughness requirements of the welded joints are achieved.

- **Weldability and Welding Process Considerations**

  When it comes to welding of connections for earthquake resistant structures, specific focus is on the matching of the strength of the welded joint with the parent steel. In the case of a seismic connection, the simple assumption, as long as the weld is "strong" enough in terms of yield and tensile strength and overmatches the adjacent parent metals, does not apply alone. The welded connection, apart from meeting minimum strength requirements and being fracture tough, is intended to make a contribution to the controlled yielding of the connection. Excessive weld metal strength and the subsequently reduced local yielding may lead to stress intensification in critical locations and may become the starting point for crack initiation.

  As the steel grade's weldability is determined by its chemical composition and grouped accordingly, welding consumables are welding process specific and classed into consumable weld groups in the relevant welding standards. These welding consumable groups are then matched with the relevant steel type and working combination are recorded in what is generally classed as prequalified welding procedures.

Qualifying welding procedures to meet specifically seismic steel requirements is a complex activity and requires the input of someone with considerable welding engineering expertise. Having qualified procedures via testing, demonstrates that the expected properties have in actual fact been achieved. Depending on the welding process and the welding parameters chosen, quite different mechanical properties may be achieved. A good example is the case of an incorrectly selected self-shielded flux cored wire which resulted in a significantly different fracture toughness value and did not meet the minimum requirements as compared to similar strength gas shielded flux cored or solid wires. Another example relates to the selection of the metal transfer mode when welding e.g. with solid wires; inappropriate selection of the mode with the associated energy input as the dip transfer is prone to deliver lack of fusion.

An important aspect for the safety of welded connections is the acceptance level of external and internal weld imperfections defined in AS/NZS 1554.1. Large scale testing of seismic moment connections performed at HERA in late 1990s confirmed that compliance with AS/NZS 1554.1, SP weld ensures adequate performance of the welds under low cyclic high-strain fatigue loadings. Therefore, welding procedures and welder qualification tests performed to overseas standards usually need to be re-qualified due to the difference in the acceptance levels for weld imperfections.

When either steel materials or welding consumables are not in conformity with the nominated Australian/New Zealand standards, prequalification of welding consumables is not possible and special welding procedure qualification tests are required to be undertaken using the methods specified in AS/NZS 1554. In this context it is also important to note that the applicable welding procedure specifications should be approved for the particular job by the Design Engineer or their nominated representative.

Fabrication Quality Management Procedures

It has been largely accepted that the quality of welding cannot be fully verified by final inspection. A process orientated quality management approach is required in order to produce consistent results for seismic applications. This approach has been implemented in the AS/NZS 1554 welding standard series, which spells out qualification of people involved in welding, welding supervision and inspection. The standard also requires fabrication to follow a suitable quality management system such as AS/NZS ISO 3834 that is also linked to NZS 3404.1:2009.

The AS/NZS 1554 series of standards covers welding fabrication and the associated quality assurance. It is important to understand that the welding procedure related aspects as discussed above are complemented by welding fabrication related quality aspects. The AS/NZS 1554 series of standards defines for the NZS 3404 designed connections the permissible level of weld imperfections and when an imperfection becomes a repairable defect. It also specifies the recommended level of Non-Destructive Testing (NDT) including the methods to be used.

HERA has demonstrated that if keeping within these limits, based on the prequalified steels and welding consumable, dependable seismic performance can be achieved. Assuming the requirements of the NZ standards are carried over 1 to 1 into an overseas production workshop, the task of demonstrating that the minimum standard requirements have been achieved is daunting. As required for local fabrication, the imported products must be supported by the specified

documentation. In the case of using unidentified steels, full material traceability documentation for all steel used and tested is required.

In HERA's view this level of inspection and documentation can only be achieved if highly experienced and trustworthy New Zealand QA representatives are present in the overseas fabrication location and are personally signing off the compliance documentation as meeting the NZ requirements.

Conclusion – Equivalence Evaluation is Complex, Risky, Time-consuming and Costly

Steel structures performed very well and above expectations in the 2010/2011 Canterbury earthquakes. This is attributed to the important research and design procedures developed from the early 1980's and was underpinned by use of dependable materials. Variable performance of steel structures in some overseas earthquakes have shown that, while steel is a very good material in severe earthquakes, it is not a miracle material and is prone to failures if poor design and construction practices are used.

The NZ design framework (NZS 3404) allows pathways for the use of fabricated imported steels based on steels not listed as prequalified in the standard. However, NZS 3404 specifically states that unidentified steels shall not be used in members of an associated structural system that are subject to inelastic demand or in members which are subject to moment redistribution, **unless it is shown by tests** that the steel complies with the requirements of steels specified for seismic members.

It also states that structural steels or shapes used, other than those referred to in the NZ framework, shall comply with an internationally recognised Standard that is approved by a qualified metallurgist or materials engineer. As noted, the approval process for unidentified steel is outside the scope of the NZ standards and requires additional expertise relating to the understanding of the New Zealand seismic design framework, not readily available by metallurgists or material engineers.

In line with NZS 3404, it is the responsibility of the design entity to ensure that all requirements are met. This is usually through the Design Engineer who is responsible for interpretation of all requirements of the standard and ultimately signs off all relevant documentation, thereby certifying the structure.

Providing documentation and full traceability for imported fabrication based on the NZ steel construction design framework requires attention to detail by experienced people and a trustworthy supply chain. We also observe that the unassured geometry and properties of imported steelwork will create the need for re-design i.e. if introduced by a contractor.

After a serious event with failure, steel properties as used can be confirmed with relative ease and those signing-off non-compliant steel can be left with serious legal exposure. The provision of unreliable documentation from some overseas suppliers is of particular concern, as it makes reliance on an overseas tested paper trail uncertain.

Due to the high incidences of unreliable documented certification relating to imported steel from non-certified sources this leaves the responsible engineer with great uncertainty as to their exposed risk and will also raise the question "is this risk insurable for them". And more general from a general

professional engineers perspective, is it is acceptable to put lives and assets at risk if this pathway is not followed carefully and completely.

This document is technical in nature and does not consider the economic aspect of imported fabrication. However, the complex issues which have to be addressed to manage imported steel work meeting NZ requirements risks add substantial cost to the import option. HERA experience has shown that if all risks are adequately addressed the gap in cost between imports and local fabrication is close.