Proposed Material Requirements for Category 3 Members in Seismic-Resisting Systems

Author: *Alistair Fussell[1], Kevin Cowie[1], Dr Michail Karpenko[2], Dr Charles Clifton[3]*
Affiliation: *[1]Steel Construction New Zealand Inc., [2]NZ Heavy Engineering Research Association, [3]Department of Civil and Environmental Engineering – University of Auckland*
Date: *August 2020*
Ref: *MAT 2002*

Keywords
Brittle fracture, Charpy V-notch impact energy, ductility, seismic-resisting system, yield strength, tensile strength

Introduction
The Steel Structures Standard material provisions for seismic applications are intended to ensure that the grade of steel chosen can meet the expected inelastic demand in both seismic and non-seismic applications (SNZ, 1997a). This includes suppressing brittle failure. The current NZS 3404 1997/2001/2007 material requirements are identical for category 1, 2, and 3 members, even though the inelastic seismic demand from category 3 members is much lower than that from category 1 and 2 members. This lack of differentiation of material requirements has created problems sourcing compliant steels for seismic-resisting systems.

In this paper, revised material selection criteria based on the NZS 3404.1:2009 (SNZ, 2009) provisions are presented for category 3 members. These requirements represent a relaxing of the NZS 3404:1997 (SNZ, 1997b) amendment 2 Table 12.4 provisions. This Steel Advisor article presents the technical basis for the revised material selection criteria and the potential benefits of adopting these requirements.

It is intended that that the proposed material requirements for category 3 members will form the basis for changes to the current NZS 3404 provisions. To this end, draft standards provisions based on the requirements presented in this paper have been included.

Steel Structures Standard Seismic Design Philosophy

The Steel Structures standard classifies seismic load resisting systems into 4 categories based on structural demand. These 4 categories are: fully ductile (category 1), limited ductile (category 2), nominally ductile (category 3) and elastic systems. In addition to categorising systems, members within seismic load resisting systems are also categorised into one of 4 categories, based on the system seismic ductility demand, and whether the member is a yielding or a protected element. As defined in the NZS 1170.5 commentary, a ductile structure (category 1-3) can dissipate energy in an earthquake and sustain, without significant loss of strength, repeated displacements of a magnitude equal to that assumed in the design for the ultimate limit state (ULS) (SNZ, 2004), as well as sustain displacements up to 1.5 times the ULS without a fundamental change of behaviour.

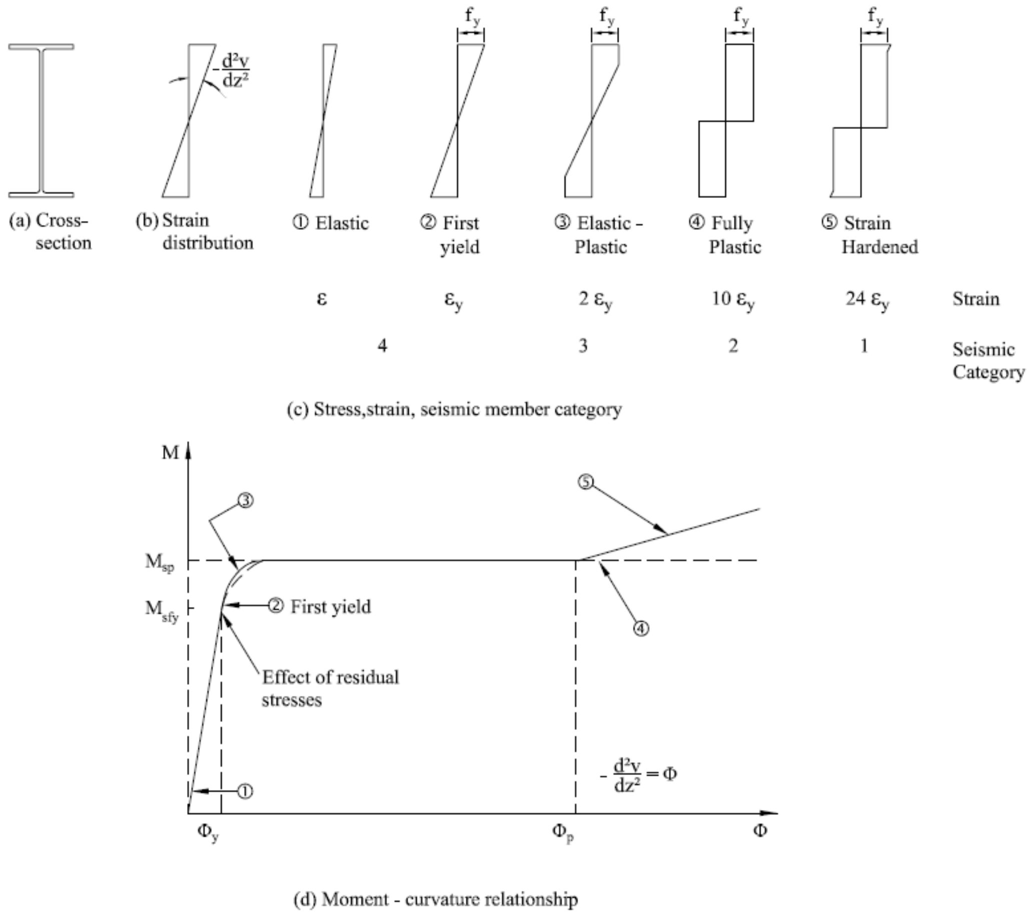
To simplify design, it is assumed that adequate ductility has been provided for seismic load resisting systems if the design and detailing rules of NZS 3404 are adhered to. These include category dependent material, section geometry, lateral restraint, and connection design action requirements. Results from past research and performance in the field (Clifton et al., 2011) show this to be the case.

A key element of the NZS 3404 seismic provisions is the application of capacity design to seismic-resisting systems, to ensure that in the event of a major earthquake, a ductile yielding mechanism can develop to prevent structural collapse. Capacity design requires the designer to select suitable ductile failure modes and then to proportion the structure to suppress other failure modes (SNZ, 2004).

The seismic demand associated with the various member categories is presented in Figure 1. The ratio of category 1 to 3 member flexural strain, and category 2 to 3 member flexural strain is approximately 12 to 1 and 5 to 1 respectively. The demand on a plastically designed member in plastic analysis is similar to that for a category 2 seismic member, however, members in plastically designed frames are typically subject to monotonic loading, in contrast to the cyclic nature of seismic loading.

Figure 1

Seismic Demand Associated with the NZS 3404 Member Categories



Note. Seismic Demand Associated with the NZS 3404 Member Categories. Adapted from "New Zealand Structural Steelwork Limit State Design Guides Volume 1" [Report] R4-80, by C. Clifton, 1994*.* Copyright 1994 by HERA.

Steels for Seismic Applications

Prior to the Northridge (1994) and Kobe (1995) earthquakes, structural engineers believed that structural steel was an inherently fracture resistant material. The unexpected examples of fracture of welded steel structures resulting from these events exposed the fallacy of this view and forced a rethink of the material requirements for structural steels used in seismic-resisting systems (Hyland et al., 2004).

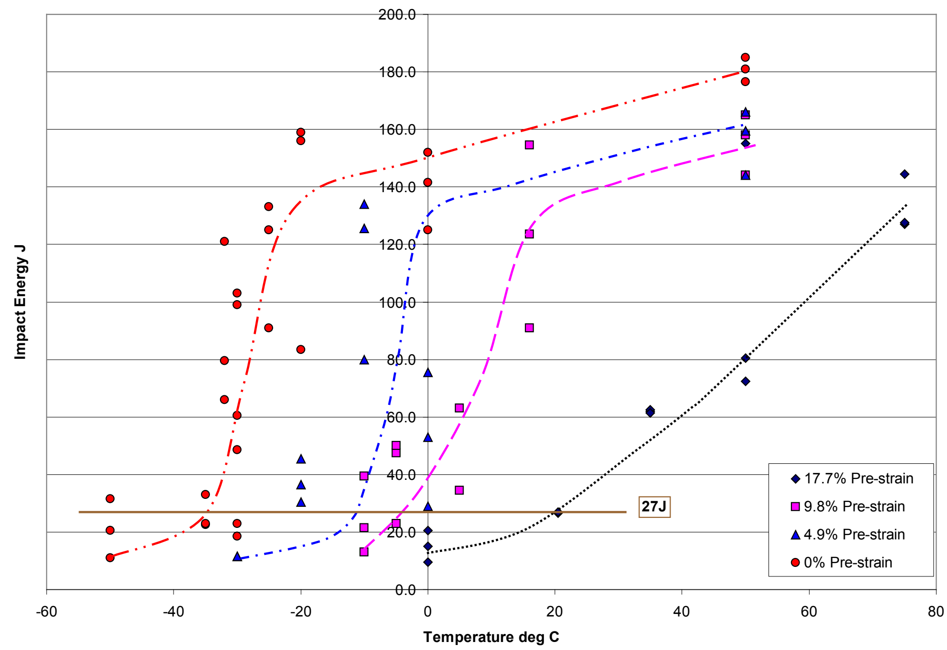
According to Kuwamura (2003), brittle fracture, which is defined as fracture with little or no plastic deformation, is a complex phenomenon that is dependent on material (yield to tensile ratio, Charpy V-notch energy, temperature, material thickness), weld (heat input, weld geometry, the use of backing bars and weld run off tabs, defects), and load factors (amplitude of response, strain rate, duration). This is an extended definition which covers both ductile overload fracture, where the material is ductile but the seismic deformation demands on the weak link in a system are so high that the strain demands exceed the fracture strain and classic brittle fracture, where the material is below the transition temperature and so not capable of inelastic response. Most so called brittle failures observed in earthquake are ductile overload fractures, however some classic brittle fractures have been observed in recent severe earthquakes (Clifton et al., 2011)

Historically, the focus of material selection criteria for seismic applications has been on the stress-strain characteristics of steels, particularly the elongation at fracture value and the yield strength to tensile strength ratio. It has been recognised that a low yield to tensile strength ratio helps increase the length of the yielding region of flexural members with a subsequent increase in their plastic rotation capacity (Hyland et al., 2004). An upper limit on the actual yield strength of members in seismic frames is also important to ensure that the strength hierarchy assumed in the capacity design process is maintained.

Little attention was given, however, to the notch toughness of steels to suppress brittle fracture during a seismic event. A review of the Charpy impact characteristics of internationally manufactured steels identified that many such steels did not possess adequate fracture toughness to avoid brittle fracture during a major earthquake event even at ambient temperature due to pre-straining and aging effects (Hyland et al., 2004). Steels in seismic-resisting systems can be pre-strained by fabrication and erection processes or by past moderate earthquake events. Based on the Charpy V-notch testing of Australian manufactured steel samples, a pre-strain of 17.7% increased the transition temperature between brittle and ductile behaviour steel approximately 55°C (Hyland et al., 2004), see Figure 2.

Figure 2

Charpy V-Notch Transition Curves Showing the Effect of Pre-strain



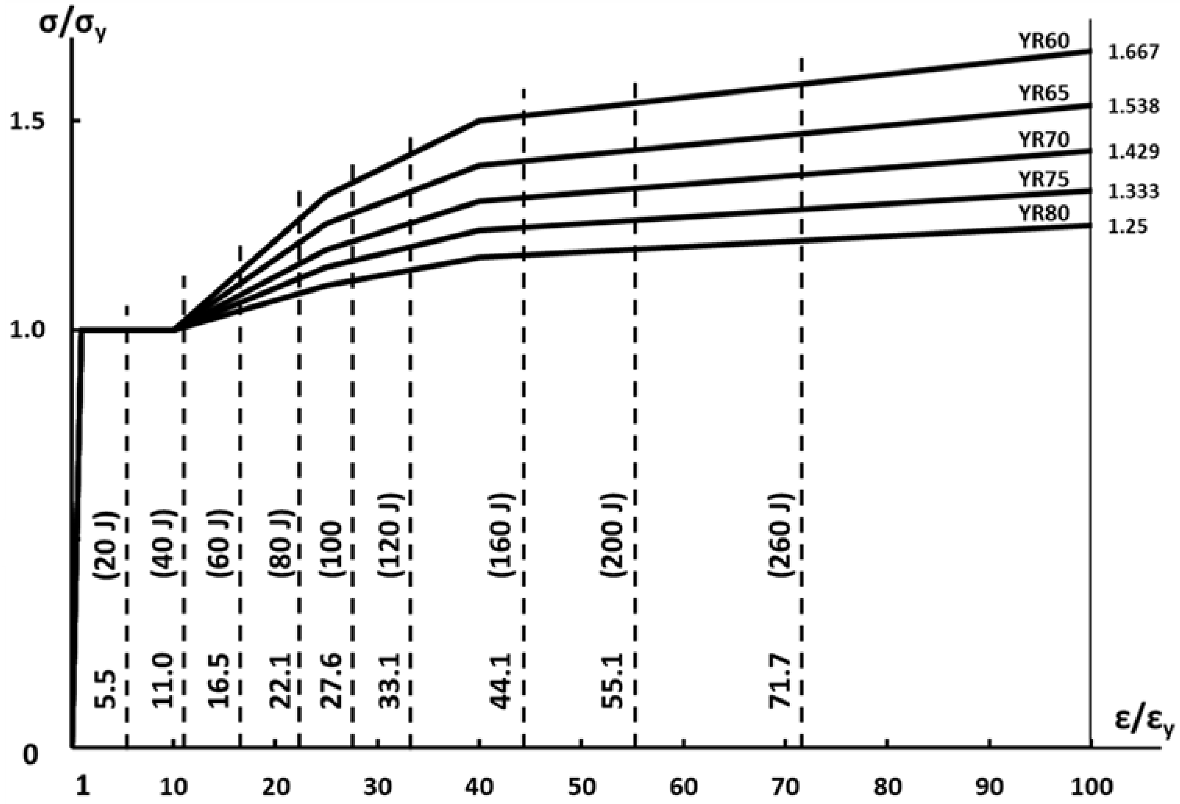
Note. Charpy V-Notch transition curves showing the effect of pre-strain. From "Selection of Structural Steels for Seismic Performance" [Paper presentation], by C. Hyland, W. Ferguson, & J. Butterworth, 2004.

Following an extensive post Kobe earthquake research programme, Japanese researchers have developed guidelines for designing moment-resisting frame welded connections to ensure they possess adequate plastic rotation capacity for the level of seismic demand. An example of such guidelines are those developed by Kuwamura (2003), a Japanese researcher who classified steels and welds into one of four categories. The material selection factors used to rank steels were yield to tensile strength ratio and Charpy V-notch impact energy. To even qualify for a material ranking under this classification system, steel must possess a low yield to tensile strength ratio (0.65-0.8) and a high Charpy V-notch impact energy (minimum 60 Joules @ 0°C). Utilising test data, a relationship has been developed between section plastic strain preceding brittle fracture and Charpy V-notch impact energy, see Figure 3.

Kuwamura's work was influential in the adoption of the 70 Joules @ 0°C Charpy V-notch impact energy limit introduced in amendment 2 of NZS 3404:1997 for category 1, 2, and 3 members. According to the HERA Limit State Design Guide (Clifton, 1994), the section strain demand associated with category 1, 2, and 3 members is $24e_y$, $10e_y$ and $2e_y$ respectively. The 70 Joules @ 0°C Charpy V-notch impact energy requirements would therefore equate to $19e_y$, or the upper end of category member 1 demand, based on the work of Kuwamura, see Figure 3. As an aside, the relaxation of the impact toughness requirements for category 3 members in NZS 3404.1:2009 is also consistent with the work of Kuwamura. The minimum Charpy V-notch impact energy requirement was reduced to from 70 to 27 joules @ 0°C, which would equate to a strain demand at brittle fracture of $7.4e_y$ according to Figure 3. This is greater than the $2e_y$ requirement assumed for category 3 members.

Figure 3

Stress-strain Curves for Different Yield Ratios and Strain Limits Governed by Charpy Impact Energy



Note. From "Classification of Materials and Welding in Fracture Consideration of Seismic Steel Frames", by H. Kuwamura, 2003, *Engineering Structures, 25*(5), p. 553. (https://doi.org/10.1016/S0141-0296(02)00166-9). Copyright 2003 by Elsevier.

In 2003, the International Institute of Welding document IIW-X-1504-03 (IIW, 2003) presented Level 1 and 2 risk assessment procedures (RAPs). The purpose was to provide a rational method by which the qualitative risk of failure of moment beam-column connections under seismic loading can be assessed. In both methods, the risk is determined as a function of the interaction of three crucial factors: stress and stain levels, flaw size and fracture toughness, considering the consequence of different fabrication details. In accordance with Level 1 procedure, the risk of brittle fracture is considered Very Low for CVN ≥ 100J, Low for 47J≤ CVN < 100J and Medium for 27J≤ CVN < 47J; where the Charpy energy requirements are minima for weld metal, HAZ or base metal at the minimum service temperature. Level 2 procedure represents a more complex assessment of risk, relying on an analytical study consisting of finite element analyses and fracture mechanics methods. The degree of risk of fracture is assessed in terms of three aspects: 1. Stress and strain levels at the joint 2. Fabrication details, flaw sizes and Non-Destructive Testing (NDT) 3. Toughness properties. One of the limitations of the IIW approach is that it covers application to members and connections in moment resistant frames only.

A detailed procedure for assessing brittle fracture has been developed by the Japan Welding Engineering Society (JWES). The WES 2808 document (JWES, 2003/2017) is based on the WES 2805 (JWES, 1976/2007) methodology that was first published in 1976 and revised in 1980 and 1997. WES 2805 generally deals with classic brittle fracture in monotonic and static loading conditions. However, investigations following a severe earthquake that struck southern Hyogo Prefecture in January 1995, indicated that brittle fractures were caused mainly by "large cyclic and dynamic strain" during seismic loading, ie by ductile overload. WES 2808, includes several improvements of the evaluation procedure; a correction of constraint loss in the fracture assessment of structural components, engineering assessments of strain concentration for various details of beam-to-column connections, and the consideration of effects of tensile and compressive pre-strains on fracture etc. WES 2808 can be applied to steel structures of bridges as well as buildings, where high strength steels of 590 MPa strength class steels are going to be widely applied in Japan. The assessment is based on two approaches: (1) a reference temperature concept for the evaluation of the material fracture toughness under cyclic and dynamic loading, and (2) an equivalent Crack Tip Opening Displacement (CTOD) concept for the correction of CTOD toughness for constraint loss in structural components. WES 2808 is utilised for fail-safe design, fabrication and maintenance of steel structures being subjected to large cyclic and dynamic strain in Japan. WES 2808 has been updated in 2017 to expand the range of use and to improve the accuracy.

A proposal for a new criterion for the choice of steel material for plastic design has been developed as a result of the European MATCH research programme (Feldmann, 2017). This criterion includes the estimation of the upper shelf limiting temperature T_{US} depending on the $T_{27}J$ -temperature to prove the qualification of the steel for the designate field of application. Using this methodology, it was determined that steels for moment resisting frames require an upper shelf toughness value of 67 Joules in the case of a ground acceleration of 0.25g, and 120 Joules for a ground acceleration of 0.35g.

The structural Eurocodes EN 1993-1-10 (CEN, 2005b) provide common rules for everyday use for the design of structures and components. Unusual forms of design or service conditions are not specifically covered. It is entirely based on fracture mechanics and has been calibrated by experiments and service experience. An initial crack is assumed at a reference detail, then crack propagation is calculated from assumed loadings, and finally the crack is assessed using the R6 failure assessment procedure. The result is a minimal usable service temperature depending on the yield stress of the steel, the Charpy-V-notch properties and the wall thickness. EN 1993-1-10 can apply for both statically and (low cycle) fatigue loaded structures. Seismic actions require a special consideration, since the plastic deformation capacity must be established. EN 1998-1 addresses the choice of material for capacity design as used for plastic hinges but provides no specific rules for the required toughness of structural steels for seismic conditions. The underlying regulations for toughness of EN 1993-1-10 apply.

At the time of writing of this publication, new rules for toughness requirements in case of seismic design have been included in 2nd draft prEN 1993-1-10. For the members subjected to seismic loading, the draft includes an upper shelf stipulation for a Charpy Impact Test requirement of 125J at a test temperature of 20°C. This approach is based on the upper-shelf toughness requirements for the design of steel structures based on damage mechanics. The proposed requirements apply to all steels manufactured to EN 10025-3, EN 10025-4, EN 10025-6, EN 10210-1 and EN 10219-1 with the exception of subgrades N, NH, M, MH, NL, NLH, ML, MLH, Q or QL. At this stage it is unclear whether the recommendations will be adopted and the possible implications for the steel supply chain.

Because of the utilisation of nominal material parameters, the toughness requirements do not only apply to the base material, but also for welds and heat affected zones. The proneness to brittle fracture is strongly connected with the existence of an initial crack and weld stress (strain) concentration factor. Structural components with initial cracks or imperfections, lead to higher toughness requirements. The presence of an undetectable crack should always be considered in welded connections. The size of this crack depends on the capability of the post-weld inspection techniques and execution (fabrication) requirements. Therefore, fabrication quality requirements should always be considered in addition to the requirements for steel.

Fabrication

Weld imperfections affect the resistance against brittle fracture in multiple ways. There is the stress raising effect of the notch associated with most imperfections and, in addition, there is the fracture mechanics effect of cracks. Some types of imperfections as cracks, lack of fusion and lack of penetration act as an initial crack, which may then propagate until final failure. It is essential that the materials selection requirements apply in combination with the execution standard AS/NZS 5131 (SA/SNZ, 2016d) and AS/NZS 1554.1 (SA/SNZ, 2014) Weld Category SP.

NZS 3404 Seismic Material Requirements

The material property requirements for seismic-resisting systems are presented in Table 12.4, NZS 3404. This table has been reproduced in Table 1.

Table 1

NZS 3404 Material for Seismic Application Requirements

Item	Category 1, 2, and 3 members	Category 4

1	Maximum specified grade reference yield stress[1]	360 MPa	450
2	Minimum % total actual elongation[2]	25	15
3	Maximum actual yield ratio (f_y/f_u)[2]	0.8	0.9
4	Maximum actual yield stress[2]	≤$1.33f_y$[4]	-
5	Minimum Charpy V-Notch impact energy[3,4]	70J @ 0 °C – Average of three tests 50J @ 0 °C – Individual test	No special provisions apply

Notes.

1. The limits in item 1 are based on grade reference steel thickness of 12<t≤20mm from the appropriate material supply standard.
2. For items 2, 3, and 4, the mechanical properties are those recorded on the certified mill test report or test certificate.
3. Charpy V-Notch testing is only required for sections greater than 12mm thick.
4. These impact energy requirements are only for steels in environments where the basic service temperature is ≥5 °C.

The seismic material requirements are intended to:

- Suppress brittle fracture of steels subject to inelastic demand and a high strain rate associated with seismic loading (see Table 12.4, item 5),
- Ensure ductile behaviour through minimum tensile elongation, maximum f_y/f_u ratio and grade yield strength requirements (see Table 12.4, items 2,3 and 1 respectively), and
- Limit member over strength capacity to ensure the strength hierarchy assumed in the capacity design process is maintained (see Table 12.4, item 4).

NZS 3404 limits the use of cold formed hollow sections in seismic applications. Such sections must not be used as category 1 members. Additionally, they must not be used as category 2 members unless their ductility capacity is established by testing or rational analysis (SNZ 1997b). In practice this limits the use of cold formed hollow sections to category 3 and 4 members, although they have been shown to be capable of significant inelastic demand under cyclic testing.

Discussion

Means of Establishing Compliance

Compliance with items 2, 3, and 4 of Table 12.4 is established from the data on a material test certificate. After publication of the latest material requirements for seismic applications in NZS 3404, a seismic steel grade S0 was introduced to the plate and hot rolled section standards AS/NZS 3678 (SA/SNZ, 2016b) and AS/NZS 3679.1 (SA/SNZ, 2016c) respectively. This steel is a deemed to comply product manufactured to the category 1,2 and 3 member requirements of Table 12.4.

Charpy Impact Requirement – Limitation of Applicability

The impact energy requirement (item 5) is only applicable for steels in an environment where the basic design service temperature is 5°C or greater. No guidance is given to determine the minimum impact energy requirement if the basic design service temperature is less than 5°C. A further point to note is that Charpy V-notch testing is only required for sections greater than 12mm thick.

Lack of Differentiation of Requirements

The NZS 3404:1997 amendment 2 features a lack of differentiation of material requirements between those for category 1, 2, and 3 members.

Steels for Seismic Applications – International Practice

Despite the flurry of international research precipitated by the Northridge and Kobe earthquakes, there is a lack of international consensus regarding material selection criteria for seismic applications.

For comparative purposes, the seismic material selection provisions for a range of international standards, codes and specifications are presented in Table 2. These provisions are discussed in greater detail in Appendix C.

Table 2

Material Selection Criteria for Seismic Applications – International Design Standards

Country or region	Specification	Maximum specified grade reference yield strength	Minimum % total actual elongation at fracture	Maximum f_y/f_u ratio	Maximum actual yield strength, f_y	Minimum Charpy V-notch energy
USA[1]	AISC 341-16	Moderate to significant seismic demand: 50 ksi (345 MPa)	-	-	-	Hot rolled sections 27 Joules @ 21°C for flange thickness greater than 38mm Plate 27 Joules @ 21°C for plate thickness greater than 50mm
		Limited in elastic action: 55 ksi (380 MPa)				
		Column[5] 70 ksi (485 MPa)				
Canada	CSA S16-19	Yielding element: 350MPa		0.85[2]		
		Columns[5]: 480 MPa				
Europe	EN 1998-1-1	EN 1993-1-1	EN 1993-1-1	EN 1993-1-1	$\leq \gamma_{ov} f_y$ ie $1.375 f_y$	EN 1993-1-10
	EN 1993-1-1[6]	460 MPa (t≤40mm)	15	0.91[2]		Min 27@ 20°C. Material selection to EN 1993-1-10
China	GB 50011		20	0.85[3]		Minimum 27J @ 0°C, see table C3 for conforming steel grade requirements[4]

Notes.

1. The rationale for the lack of ductility requirements in AISC 341-16 is discussed in Appendix C.
2. The f_y/f_u ratio is determined from the grade minimum yield and tensile strength values specified in the relevant steel standards.
3. The f_y/f_u ratio is computed from the mechanical properties reported on a material test certificate.
4. Conforming steel grades are Q235 B, C, & D and Q345 B, C, & D.
5. Columns are subject to low inelastic demand.
6. Steels manufactured to European steel standard EN 10025 have an upper limit on the actual tensile strength of steels produced to this specification

Discussion

Differentiation of Requirements

There is limited differentiation of material requirements based on seismic demand. The only example of such differentiation is the specification of a maximum grade reference yield strength for yielding and column elements of seismic-resisting systems.

Charpy V Notch Properties

The Charpy V Notch requirements stipulated in international design standards are much lower than Japanese practice for welded structures and the 70 Joules @ 0°C specified in NZS 3404:1997 amendment 2 for category 1,2 and 3 members. NZS 3404.1:2009 limited the range of steel grades for use as category 3 members to those with a guaranteed minimum Charpy V Notch value of 27 J @ 0°C. Such steels would meet the Charpy impact requirements of all the international codes referenced in Table 2.

Limits on the Actual Properties of Steels
Aside from a limit on the maximum tensile strength of steels manufactured to EN 10025, there are no limits specified on either the actual yield or tensile strength reported on a test certificate. Furthermore, compliance with the f_y/f_u ratio limit for the most part, is established from the minimum grade values specified in the relevant steel standard.

Proposed Category 3 Member Requirements

The proposed category 3-member material requirements presented in this section are based on the NZS 3404.1:2009 provisions. These requirements are categorised as ductility and fracture toughness material selection criteria.

Ductility Requirements

Steels for category 3 members shall satisfy the ductility requirements in Table 3.

Table 3

Proposed Category 3 Member Material Ductility Requirements

Item		Category 3 Members
1	Maximum specified grade reference yield strength	360
2	Minimum % total actual elongation at fracture	15[1]
3	Minimum f_u/f_y ratio	1.2[2](1.1)[3]

Notes.
1. The mechanical properties are those recorded on the certified mill test report or test certificate.
2. The yield and tensile strength values are the minimum grade values specified in the relevant steel standard.
3. The bracketed value is applicable if compliance is established from the mechanical properties on a material test certificate.

It is proposed to allow two routes for establishing compliance with the requirements of Table 3, these are:

1. Specify a conforming steel type, or
2. Establish conformance from the mechanical properties recorded on a material test certificate

A list of conforming steel types is presented in Table 4. The NZS 3404.1:2009 table 2 steel type relationship to steel grade applies to Table 4.

Table 4

Conforming Steel Types Satisfying Material Ductility Requirements.

Steel Type[1]	Exclusions
2[3]	AS/NZS 1163 SHS and RHS sections[2]
2S	-
3	-
5[4]	AS/NZS 1163 SHS and RHS sections
5S	
6	

Notes.
1. Steel types with no minimum V Notch Charpy impact requirement have been excluded
2. The minimum grade elongation at fracture values for a range of SHS and RHS sections manufactured to AS/NZS 1163 (SA/SNZ, 2016a) do not comply with the proposed 15% elongation at fracture limit. Compliance for this product range must be established in accordance with the values on a material test certificate.
3. EN 10219 S275J0 grade is a type 2 steel. The minimum grade elongation at fracture values comply with the proposed 15% elongation limit.
4. EN 10219 S355J0 grade is a type 5 steel. The minimum grade elongation at fracture values comply with the proposed 15% elongation limit.

Charpy V-notch Toughness Requirements

Steels for applications that satisfy the requirements of Table 5 shall have a minimum Charpy V-notch impact energy of 27 Joules @ 0°C.

Table 5

Limits of Applicability - Deemed to Comply Impact Property Requirement – No Pre-strain

Steel type[1,2,3]	Product type	Minimum design service temperature[4]	Maximum steel thickness (mm)	Fabrication and construction induced pre-strain (%)[5]
2	Cold formed CHS	5 °C	40	0
2	Cold formed RHS/SHS	5 °C	24	0
2	Hot formed section and plate	5 °C	45	0
5	Cold formed CHS	5 °C	23	0
5	Cold formed RHS/SHS	5 °C	17	0
5	Hot formed section and plate[7]	5 °C	36	0

Notes.

1. Refer table NZS 3404.1:2009 for steel type to steel grade relationship. EN 10219 S275 J0 and S355 J0 grades are type 2 and 5 steels respectively
2. Type 2S, 3, 5S, and 6 steels may also be used for category 3 members
3. The design service temperature is computed using NZS 3404 section 2.6.3
4. This only includes post manufacturing plastic strain; those associated with cold forming the section have already been considered.

Steels for applications outside the scope of Table 5 shall be selected using the methodology of Hobbacher and Karpenko (2020). To request a copy of this paper, contact HERA at (09) 262 2885. The intention is to include the approach of Hobbacher and Karpenko as an alternative material selection method in the NZS 3404 appendices. This will provide material selection solutions for applications outside the range of applicability of the current NZS 3404 provisions and address some of the anomalies in the current requirements noted in the next section.

Basis for Table 5 Impact Property Requirements

The Table 5 impact property requirements have been derived from the work of Hobbacher and Karpenko (2020). In their paper (Hobbacher & Karpenko, 2020), tabulated values of maximum steel thickness for a minimum design service temperature and steel grade are presented for seismic and non-seismic applications.

The paper considers two stress usage levels expressed as a proportion of yield strength (f_y) for non-seismic applications, $0.5f_y$ and $0.75f_y$, with an allowance of 100 MPa for residual stresses. Three different levels of seismic verification are included: verification modes I, II, III, which correspond to category 4, category 3, and category 1/2 member seismic demand respectively. The selection tables for non-seismic applications cover a range of AS/NZS, JIS, EN, and API standard steel grades, while the seismic application material selection tables are limited to AS/NZS standard steel grades. All steels in the study have minimum grade Charpy V Notch impact energy requirements.

To address the lack of non-AS/NZS standard steel grade material selection data for seismic applications in the work of Hobbacher and Karpenko (2020), a process of establishing equivalent brittle fracture performance between AS/NZS standard steel and non-AS/NZS standard steel grades has been undertaken. The process involves comparing the maximum steel thickness for a given minimum design service temperature and section stress usage level of $0.75f_y$ (non-seismic applications) for a range of steel standard grades. An equivalent non-AS/NZS steel standard grade has been defined as having a greater or comparable maximum steel thickness for a given design service temperature to that for a similar AS/NZS standard steel grade. Similarity is based on minimum grade yield strength and minimum V Notch Charpy impact properties. The rationale for this approach is that similar non-seismic brittle fracture performance would equate to similar seismic brittle fracture performance.

The comparative exercise identified some anomalies in the NZS 3404 steel type relationship to steel grade provisions. These anomalies include:

1. Classifying cold formed and hot formed sections with identical or similar minimum grade yield strength as the same steel type (steel types 2 and 5). This neglects the reduction in maximum steel thickness for a given minimum design service temperature due to the introduction of bending strains during the cold

forming process to manufacture hollow sections. This reduction is more pronounced for SHS and RHS sections compared to CHS sections, due to the smaller bend radii required for such sections.

2. Steel grades with reasonably different minimum yield strength requirements have been classified as the same steel type e.g. 250L0 and 300L0 (type 2 and 3 steels).

In-spite of these anomalies, it is not proposed to change the NZS 3404 steel type relationship to steel grade requirements as these same provisions are included in AS/NZS design (AS/NZS 5100.6 [SA/SNZ, 2017]) and welding (AS/NZS 1554.1 [SA/SNZ, 2014]) standards. The approaches recommended in this paper to address anomaly 1 and 2 are:

Anomaly 1: Vary the limitations of applicability in Tables 5 within the same steel type (steel type 2 and 5) based on the method of product manufacture and hollow section shape
Anomaly 2: Base the steel type 2 and 3 hot formed section and plate limits of applicability on the highest strength grade (f_y=300 MPa). This approach is considered reasonable as the use of grade 250 plate is limited and this strength grade has been removed from the hot rolled section standard (AS/NZS 3679.1 (SA/SNZ, 2016c)).

Cold formed hollow sections manufactured to EN 10219 (CEN, 2006) are increasingly used in New Zealand building and infrastructure projects. EN 10219 steel grades are currently not included in the NZS 3404 steel type relationship to steel grade provisions. The work of Hobbacher and Karpenko (2020 has demonstrated the equivalence of comparable EN 10219 and AS/NZS 1163 (SA/SNZ, 2016a) steel grades. The equivalent grades are listed in table 6.

Table 6

Equivalent steel grades for material selection to avoid brittle fracture purposes

AS/NZS 1163	EN 10219
250L0	S275J0
350L0	S355J0

Discussion of Proposed Category 3 Member Material Requirements

The proposed requirements represent a relaxing of the ductility and impact toughness requirements of NZS 3404:1997 amendment 2. In particular, the following changes have been proposed for category 3 members:

1. Slight decrease in the f_u/f_y ratio from 1.25 to 1.2
2. Removal of the upper yield strength limit
3. Decrease in the elongation at fracture value from 25% to 15%
4. Change in the means of establishing compliance with the minimum f_u/f_y ratio. There is an option to use a conforming steel approach that will eliminate the requirement to specifically check the values on a material test certificate with the seismic material requirements of the standard
5. Reduction in the Charpy V-notch impact energy requirement from 70 Joules to a minimum of 27 Joules @ 0^{o}C

Draft standards provisions based on the proposed category 3 member material requirements have been prepared, see Appendix A.

The technical basis for the proposed material selection criteria is presented in the next section.

Technical Basis for Proposed Requirements

The Seismic Demand Warrants a Relaxation of Requirements

The reduced seismic demand on category 3 members in seismic resisting systems warrants less onerous material requirements than those for category 1 and 2 members. This approach is consistent with that of the NZS 3404 seismic provisions as well as Japanese research (Kuwamura, 2003) and that of Hobbacher and Karpenko (2020). In NZS 3404, the design and detailing requirements become more onerous as the seismic-resisting system inelastic demand increases. Some examples of this approach include the differentiated system and member category requirements for section geometry, axial load limits, connection design actions, yielding region lateral restraint, and overstrength factors.

The proposed differentiation of material requirements for category 3 members from those for category 1 and 2 members is also consistent with NZS 3404 revisions prior to (NZS 3404:1992, NZS 3404:1997 amendment 1) and, subsequent to (NZS 3404.1:2009) NZS 3404:1997 amendment 2.

Proposed Requirements are Based on NZS 3404.1:2009

The proposed category 3 member material requirements are based on the most recent version of NZS 3404, Part 1:2009 and, therefore, represent the most up-to-date provisions. While this standard has been subsequently withdrawn following the citing of AS/NZS 5131 (SA/SNZ, 2016d), this standard followed a full standards committee and public consultation process.

A point to note is that NZS 3404.1:2009 uses a conforming steel type approach to selecting steels for category 3 seismic members. In spite of this approach, ductility and impact toughness requirements can be inferred from the grade requirements for the conforming steels. These inferred properties associated with each conforming steel grade are presented in Appendix B. A summary of these properties along with those proposed in this paper for category 3 members are presented in Table 7 for comparative purposes. The proposed requirements meet three out of four NZS 3404.1:2009 inferred category 3 member selection criteria, items 1, 2, and 4 from Table 7, while the limit on a fourth item, f_u/f_y, is essentially the same i.e. 1.23 vs 1.2 (2.5% difference).

Table 7

Inferred Category 3 Member Material Requirements for Conforming Steel Types in Table 1 NZS 3404.1:2009

Item		NZS 3404.1:2009 Category 3 member requirements (inferred)	Proposed category 3-member material requirements
1	Maximum specified grade reference yield strength	365[1] MPa	360 MPa
2	Minimum % total actual elongation at fracture	12 (15)[2]	15
3	Minimum f_u/f_y ratio	1.23[3,4,5]	1.2
4	Minimum Charpy V-notch impact value	27 Joules @ 0°C	Min. 27 Joules @ 0°C

Notes.

1. The maximum specified grade reference yield strength is associated with SM 520B JIS G 3106 (JIS, 2015) steel of thickness t≤16mm.
2. The unbracketed value is associated with C350L0 AS/NZS 1163 SHS and RHS sections. The bracketed value is related to C350L0 AS/NZS 1163 CHS sections and all other category 3-member conforming steel grades in table 1 NZS 3404.1:2009.
3. Minimum f_u/f_y ratio is based on the minimum grade tensile and yield strength values specified in the relevant steel standard, only SN 400B JIS G 3136 (JIS, 2012) steel is required to meet a tensile strength to yield strength ratio value based on the mechanical properties recorded on a material test certificate.
4. Steels manufactured to EN 10025 (CEN, 2005c) and JIS G 3106 have an upper limit on the actual tensile strength.
5. Steels manufactured to JIS G 3136 (JIS, 2012) have an upper limit on the actual yield and tensile strengths.
6. In conjunction with the proposed material requirements, it is important that fabrication complies with AS/NZS 5131 Construction Category CC2 or higher and welding with AS/NZS 1554.1. Weld category is SP to AS/NZS 1554.1 or Weld Quality Level C to AS/NZS ISO 5817. No lack of fusion or incomplete penetration is allowed in butt welds.

Ductility Requirements Meet Key NZS 3404 Plastic Design Material Provisions

The proposed ductility requirements also meet some of the key NZS 3404 material provisions for plastically designed members. The stress-strain characteristics of steel members in which plastic hinges will form must meet the requirements of Table 8.

Table 8

Material Ductility Requirements for Plastically Designed Members

Item		Plastic design limit (equivalent to category 2-member inelastic demand)
1	Yield plateau length	6 times the yield strain (6e_{y})
2	Minimum f_u/f_y	1.2[1]
3	Minimum elongation at fracture	15%

Note. The tensile strength to yield strength ratio is computed using the minimum grade values in the relevant steel product standard

In addition to the stress-strain characteristics, a grade yield strength upper limit of 350 MPa also applies.

As discussed previously, the inelastic demand associated with a plastic hinge in a plastically designed member is similar to that of a category 2 member, but with a difference in the type of loading. Plastically designed members are subject to monotonic loading in contrast to the cyclic nature of earthquake loading. Notwithstanding this difference, at the level of inelastic demand associated with category 3 members, the member would be capable of sustaining numerous cycles of inelastic action (Seal et al., 2009).

State of the Art Fracture Toughness Requirements

The major departure from the NZS 3404:1997 amendment 2 and NZS 3404.1:2009 fracture toughness requirements is the adoption of a state-of-the-art material selection to avoid brittle fracture methodology (Hobbacher & Karpenko, 2020). The proposed methodology is more nuanced than that presented in either NZS 3404:1997 amendment 2 or NZS 3404.1:2009. Rather than specifying a single minimum Charpy V Notch value regardless of the application, the fracture mechanics model adopted by Hobbacher and Karpenko considers, amongst other things, the following factors:

1. Material properties
2. Material thickness
3. Weld details
4. Weld imperfections (undetectable crack size)
5. Design service temperature
6. Seismic strain rates
7. Bending strain introduced during the manufacture of cold formed hollow sections and fabrication and construction processes

In practice, subject to satisfying design service temperature, pre-strain, and material thickness criteria, the minimum NZS 3404.1:2009 requirement of, 27 joules @ 0ºC will apply.

Implications of Material Requirements

The proposed conforming steel grade approach will simplify the process of sourcing steels for seismic applications as it aligns the category 3 member material requirements to a range of seismic and non-seismic steel grades manufactured to local and international steel standards. No additional check will be required of material test certificate data to ensure the f_y/f_u, elongation at fracture and fracture toughness values adhere to those in the seismic material provisions of the standard.

Furthermore, increasing the number of steel grades that comply with the relaxed material selection criteria, will increase the supply of compliant product. Presently there is only one steel grade, S0, in two AS/NZS standards (AS/NZS 3678 [SA/SNZ, 2016b] and AS/NZS 3679.1 [SA/SNZ, 2016c]) that comply with the NZS 3404 Table 12.4 category 3 material requirements. There is only a limited range of product and strength grades supplied to S0 grade. Consequently, it is problematic to source cold formed hollow sections and grade 350 plate for welded sections. These section types are commonly used as category 3 member columns in seismic-resisting systems.

Next Steps

The goal of this paper is to provide a technical basis for revising the category 3 member material for seismic application provisions in NZS 3404. To this end, the following steps are proposed:

Step 1 Stakeholder consultation

SCNZ will initiate a formal stakeholder consultation process that will involve widely disseminating this discussion document and publicising the start and end dates of the comments period. Stakeholders will include NZS 3404 committee members, practicing engineers, and steel distributors.

Step 2 Submit the revised category 3 member material provisions to the NZS 3404 committee

Standards New Zealand are developing a proposal to revise NZS 3404: 1997. Once the NZS 3404 standards committee has been convened, the revised category 3 member material requirements will be submitted for their consideration.

Conclusions

The current NZS 3404:1997 amendment 2 material selection criteria are identical for category 1, 2, and 3 members in seismic-resisting systems. This lack of differentiation of material requirements for category 1, 2 and 3 members is out of step with previous and subsequent revisions of NZS 3404. A relaxation of the NZS 3404 materials provisions is therefore warranted due to the low seismic demand experienced by category 3 members compared to that experienced by category 1 and 2 members.

Draft material selection criteria for category 3 seismic members have been proposed. The proposed ductility requirements are similar to those in NZS 3404.1:2009 and some international steel design codes. The fracture toughness requirements are based on a fracture model that considers some of the key variables that contribute to the brittle fracture of structural steels.

If adopted in the next revision of NZS 3404, the proposed material requirements would simplify the process of sourcing of steels for category 3 members as it would align the seismic material requirements with those of a range of seismic and non-seismic steel grades, including cold formed hollow sections. No additional check will be required of material test certificate data to ensure the key mechanical properties of the steel adhere to those in the seismic material provisions of the standard. The increased range of complying steel grades would also improve the supply of steels for category 3 members.

References

AISC. (2016a). *Prequalified connections for special and intermediate steel moment frames for seismic applications, including supplement no.1* (ANSI/AISC 358-16, ANSI/AISC 358s1-18).

AISC. (2016b). *Seismic provisions for structural steel buildings* (ANSI/AISC 341-16).

ASTM International. (2015). *Standard specification for structural steel shapes* (ASTM A992/A992M-11).

AWS. (2016). *Structural welding code – seismic supplement* (AWS D1.8/D1.8M-2016).

Canadian Standards Association. (2019). *Design of steel structures* (CSA S16).

CEN. (2004). *Eurocode 8: Design of structures for earthquake resistance: Part 1: General rules, seismic actions and rules for buildings* (EN1998-1). European Committee for Standardization.

CEN. (2005a). *Eurocode 3: Design of steel structures: Part 1-1: General rules and rules for buildings* (EN 1993-1-1). European Committee for Standardization.

CEN. (2005b). *Eurocode 3: Design of steel structures: Part 1-10: Material toughness and through thickness properties* (EN 1993-1-10). European Committee for Standardization.

CEN. (2005c). *Hot rolled products of structural steels: Part 2: Technical delivery conditions for non-alloy structural steels* (EN 10025-2). European Committee for Standardization.

CEN. (2006). *Cold formed welded structural hollow sections of non-alloy and fine grain steels: Part 1: Technical delivery conditions* (EN10219-1). European Committee for Standardization.

Clifton, G.C. (1994). *New Zealand structural steelwork limit state design guide* [report]. Volume 1, R4-80. HERA.

Clifton, G. C., Bruneau, M., MacRae, G.A., Leon, R., & Fussell, A. (2011). Steel structures damage from the Christchurch Earthquake series of 2010 and 2011. *Bulletin of the New Zealand Society for Earthquake Engineering, 44*(4), 297-318.

Feldmann, M., Hoffmeister, B., Schaffrath, S., Bartsch, H., Muenstermann, S., Yidu, D., Hoppe, B., & I, Vayas I., Avgerinou, S., Salvatore, W., & Caprili, S., Mussini, N., & Karamanos, S., Perdikaris, P., Chatzopoulou, G., Papatheocharis, T., Lindstrom, B., & de Pasquale, E. (2017). *Material choice for seismic resistant structures (MATCH)* (1831-9424). Publications Office of the European Union. https://doi.org/10.2777/482642

GB. (2010). *Code for seismic design of buildings* (50011). Ministry of Housing and Urban-rural Construction of the People's Republic of China; General Administration of Quality Supervision, Inspection and Quarantine of the People's Republic of China.

GB. (2018). *High strength low alloy structural steels* (GB/T 1591). State Market Regulatory Administration; Standardization Administration of China.

Hobbacher A., & Karpenko, M. (2020). *Provisions for avoiding brittle fracture in steels used in Australasia X-1965r2-2020*. International Institute of Welding.

Hyland, C., Ferguson, W.G., & Butterworth, J.W. (2004). *Selection of structural steels for seismic performance* [Paper presentation]. New Zealand Metals Industry Conference 2004, Christchurch, New Zealand.

International Institute of Welding (IIW). (2003). *Recommendations for assessment of risk of fracture in seismically affected moment connections*. (IIW-X-1504-03).

Japan Welding Engineering Society (JWES). (1976/2007). *Method of assessment for flaws in fusion welded joints with respect to brittle fracture and fatigue crack growth: Parts 1-4* (WES2805: 1-4).

JWES. (2003/2017). *Method of assessing brittle fracture in steel weldments subjected to large cyclic and dynamic strain: Parts 1-6.* (WES2808: 1-6).

JIS. (2012). *Rolled steels for building structure* (JIS G 3136) Japanese Standards Association.

JIS. (2015). *Rolled steels for welded structure* (JIS G 3106). Japanese Standards Association.

Kuwamura, H. (2003). Classification of materials and welding in fracture consideration of seismic steel frames. *Engineering Structures, 25*(5), 547-563.

SA/SNZ. (2014). *Structural steel welding: Part 1: Welding of steel structures* (AS/NZS 1554.1). Standards Australia; Standards New Zealand.

SA/SNZ. (2016a). *Cold-formed structural steel hollow sections* (AS/NZS 1163). Standards Australia; Standards New Zealand.

SA/SNZ. (2016b). *Structural steel – hot-rolled plates, floorplates and slabs* (AS/NZS 3678). Standards Australia; Standards New Zealand.

SA/SNZ. (2016c). *Structural steel: Part 1: hot-rolled bars and sections* (AS/NZS 3679.1). Standards Australia; Standards New Zealand.

SA/SNZ. (2016d). *Structural steelwork – fabrication and erection* (AS/NZS 5131). Standards Australia; Standards New Zealand.

SA/SNZ. (2017). *Bridge design. Part 6: Steel and composite construction* (AS/NZS 5100.6). Standards Australia; Standards New Zealand.

Seal, C.K., Hodgson, M.A., Clifton, G.C., & Ferguson, W.G. (2009). A novel method for predicting damage accumulation in seismically deformed steel. *Journal of Constructional Steel Research, 65*(12), 2157-2166.

SNZ. (1997a). *Commentary to the steel structures standard, including amendments: Part 2* (NZS 3404). Standards New Zealand.

SNZ. (1997b). *Steel structures standard, including amendments: Part 1* (3404). Standards New Zealand.

SNZ. (2004). *Structural design actions: Part 5: Earthquake actions – New Zealand* (NZS 1170.5). Standards New Zealand.

SNZ. (2009). *Steel structures standard: Part 1: Materials fabrication and construction* (NZS 3404.1: 2009). Standards New Zealand.

Appendix A

Draft Category 3 Member Material Provisions

A.1 Material Requirements

A.1.1 General

Steels used as category 3 seismic members must conform with the requirements in sections A.1.2 and A.1.3.

A.1.2 Ductility Requirements

A.1.2.1

Steels shall satisfy the ductility requirements in Table A1.

Table A1

Material Ductility Requirements

Item		Category 3 Members
1	Maximum specified grade reference yield stress	360
2	Minimum % total actual elongation	15
3	Minimum f_u/f_y ratio[1]	1.2 (1.1)[2]

Notes.

1. The yield and tensile strength values are the minimum grade values in the relevant steel standard.
2. The bracketed value is used if compliance is established from the values on a material test certificate.

A.1.2.2

Steel conforming with one of the steel types listed in Table A2 shall be accepted as satisfying the requirements of A1.2.1.

Table A2

Conforming Steel Types Satisfying Table A1 Ductility Requirements

Steel Type[2]	Exclusions
2	AS/NZS 1163 SHS and RHS sections[1]
2S	-
3	-
5	AS/NZS 1163 SHS and RHS sections[1]-
5S	-
6	-

Notes.

1. The minimum grade elongation at fracture values for a range of SHS and RHS sections manufactured to AS/NZS 1163 do not comply with the proposed 15% elongation at fracture limit. Compliance for this product range must be established in accordance with clause A1.2.2
2. The steel type relationship to steel grade relationship of table 2.6.4.4 is applicable. EN 10219 S275L0 and S355J0 steel grades are type 2 and 5 steels respectively.

A1.2.2

Alternatively, compliance with the ductility requirements of Table A1 may be established from the mechanical properties recorded on a material test certificate.

A1.3 Fracture Toughness

The material shall have adequate fracture toughness to avoid brittle fracture under the anticipated design and fabrication conditions. This includes seismic demand, design temperature, and pre-strain due to fabrication and/or construction processes (if applicable).

This clause is satisfied if the material meets the requirements of either Section A1.4 or Appendix X.

A1.4 Selection of materials for fracture toughness -Simplified method

Steels that satisfy the requirements of table A3 shall have a minimum Charpy V-notch impact energy of 27 Joules @ 0°C.

Table A3

Limits of Applicability of Simplified Selection of Materials for Fracture Toughness Methodology

Steel type	Product type	Minimum design service temperature	Maximum steel thickness (mm)	Fabrication and construction induced pre-strain (%)
2	CHS	5 °C	40	0
2	RHS/SHS	5 °C	24	0
2	Hot formed plate and sections	5 °C	45	0
5	CHS	5 °C	23	0
5	RHS	5 °C	17	0
5	Hot formed plate and sections	5 °C	36	0

Notes.

1. Type 2S, 3, 5S, and 6 steels will be suitable for category 3 members
2. EN 10219 S275J0 and S355 J0 grades are steel type 2 and 5 respectively

Steels for applications outside the scope of Table A3 shall be selected in accordance with the Appendix X provisions.

Appendix X

Selection of materials for fracture toughness – Advanced method

X.1 General

The advanced material selection method shall be used to select a suitable grade of steel from those listed in table 2.6.4.4. These provisions are applicable to welded category 3 (seismic application) members.

X.2 Procedure

X.2.1

The steel shall be selected taking into account the following:

- i) Steel material properties
  - a. Yield strength (f_y)
  - b. Minimum grade impact energy value (27 joules, 40 joules, 47 joules)
- ii) Element thickness (t)
- iii) Cold forming
- iv) Design service temperature

X.2.2 Selection of steel type

The steel type for the material thickness and product manufacturing process shall be selected from table A4 so that the lowest service temperature listed is lower than the modified design service temperature (T_{Ed}) determined in accordance with X.2.3.

X.2.3 Modified design service temperature

The modified design service temperature shall be determined using equation (A1)

$$T_{Ed} = T_{md} + \Delta T_{\varepsilon,cf,EXC} \quad \text{[Eqn. A1]}$$

Where

T_{Ed} is the modified design service temperature

T_{md} is the design service temperature specified in clause 2.6.3 NZS 3404

$\Delta T_{\varepsilon,cf,EXC}$ is the temperature adjustment for cold forming during fabrication and/or construction processes (if required), see X.2.4

X.2.4

$\Delta T_{\varepsilon,cf,EXC} = 3.\varepsilon_{cf}$ (for cold formed) or [Eqn. A2a]

$\Delta T_{\varepsilon,cf,EXC} = 1.5.\varepsilon_{cf}$ (for hot formed or heat treated after cold forming) …….. [Eqn. A2b]

Where

ε_{cf} is the degree of cold forming expressed as a percentage

X.2.5 Selection of steel grade

The steel grade shall be selected from the required steel type given in table 2.6.4.4

Table A4

Maximum Steel Thickness at Lowest Service Temperature for Category 3 Members

Steel type	Product type	Lowest service temperature (°C)													
		10	0	-10	-20	-30	-40	-50	-60	-70	-80	-90	-100	-110	-120
2	CHS	44	35	29	24	21	17	15	13	11	10	9	8	-	-
2	SHS/RHS	26	22	19	18	16	14	12	10	9	8	-	-	-	-
2	Hot formed plate and sections	49	40	32	26	22	18	15	12	10	9	8	7	6	5
3	Hot formed plate and sections	66	54	43	36	29	24	20	16	14	12	10	8	7	6
5	CHS	25	21	17	14	11	9	8	6	5	4	3	-	-	-
5	RHS/SHS	18	15	12	10	8	7	5	4	3	-	-	-	-	-
5	Hot formed plate and sections	39	32	25	21	17	14	11	9	8	6	5	4	3	-
6	Hot formed plate and sections	53	43	35	28	23	19	15	13	10	8	7	6	5	4

Notes.

1. The basis for table A4 is discussed in Hobbacher and Karpenko (2020). The tabulated values include allowance for bending strains associated with the manufacture of cold formed hollow sections, material variability and category 3 member seismic demand. Adapted from "Provisions for Avoiding Brittle Fracture in Steels Used in Australasia," by A. Hobbacher and M. Karpenko, 2020, International Institute of Welding. Copyright 2020 by the International Institute of Welding.
2. The tabulated values correspond to seismic verification mode II
3. Type 2S and 5S steel types are suitable for category 3 members subject to the limitations of note 6, table 12.4
4. EN 10219 S275J0 and S355 J0 steel grades are type 2 and 5 steels respectively

Appendix B

Inferred Material Properties – Category 3 Members NZS 3404.1:2009

Steel Standard	Form	Grade	f_y	f_u	f_u/f_y	Minimum elongation at fracture %	Minimum Charpy V-Notch Energy
AS/NZS 1163	Hollow section – CHS	C350L0[2]	350	430	1.23[1]	16-20	27 Joules @ 0ºC
	Hollow section – RHS/SHS	C350L0	350	430	1.23[1]	12-16	
AS/NZS 3678	Plate	WR350L0	350[3]		1.25[1,4]	20	
AS/NZS 3679.1	Flats and sections	G300L0[2]	300[3]	440	1.37[1,4]	22	
		G350L0	350[3]	480	1.33[1]	20	
EN 10025	Flat and sections	S275J0	275[5]	410 - 560[6]	1.49[1,5]	19-23[7]	
		S355J0	355[5]	470 - 630[6]	1.32[1,5]	18-22[7]	
JIS G 3106	Flat, sections, plate and strip in coil	SM 400B	245[5]	410-510	1.63[1,5]	18-24[7]	
		SM490B	325[5]	490 - 610	1.51[1,5]	17-23[7]	
		SM 490YB	365[5]	490 - 610	1.34[1,5]	15-21[7]	
		SM 520B	365[5]	520 - 640	1.42[1,5]	15-21[7]	
JIS G 3136	Flat, sections, plate and strip in coil	SN 400B	235-355[8]	400 - 510	1.25[9]	18-24[7]	

Notes.

1. The yield and tensile strength values are the minimum grade values specified in the relevant steel standards.
2. Grade G250L0 AS/NZS 3679.1 is no longer available in the latest version of the quoted steel standard. Grade C250 ASNZS 1163 product, while still recognised in AS/NZS 1163, is typically no longer manufactured.
3. Grade minimum yield strength based on material thickness limits; 12<t≤20mm for WR350L0 AS/NZS 3678 and 11<t≤17mm for G300L0 and G350L0 AS/NZS 3679.1 steels.
4. Tensile to yield strength ratio is based on the minimum grade yield strength associated with steel thickness limits; t≤12mm for WR350L0 AS/NZS 3678 and t≤12mm for G300L0 and G350L0 AS/NZS 3679.1.
5. Minimum grade yield strength applicable for material thickness t≤16mm.
6. Tensile strength range applicable for material thickness 3≤t≤100mm.
7. Minimum elongation at fracture values applicable for material thickness 3≤t≤100mm.
8. An upper limit on the yield strength is applicable for material thickness 16≤t≤ 100mm.
9. The limit on f_u/f_y ratio is based on the values recorded on the material test certificate.

Appendix C

Background to the Materials for Seismic Applications in International Codes

North America

The primary US code for the seismic design of steel structures is AISC 341-16 (AISC, 2016b). This specification adopts a conforming structural steel standard/specification approach. Plate, hot rolled sections, and hollows sections must satisfy the requirements of one of the acceptable ASTM specifications listed (AISC, 2016b). Limited material requirements in Table 2, such as limits on the maximum grade yield strength for primary and secondary members in seismic-resisting systems, may reduce the range of acceptable steel grades from the list of conforming specifications. The impact toughness requirements are minimal, with a modest minimum Charpy V-Notch impact value for sections and plates that exceed a minimum material thickness criterion, see Table 2.

There are no mandatory requirements specified in AISC 341-16 pertaining to an upper limit on actual yield strength, the maximum yield to tensile strength ratio and a minimum elongation at fracture value. The rationale for the omission of such limits is given the seismic code commentary (AISC, 2016b).

> The acceptable structural steels that are explicitly permitted for use in seismic applications have been selected based on their inelastic properties and weldability. In general, they meet the following characteristics: (1) a pronounced stress-strain plateau at the yield stress; (2) a large inelastic strain capability [e.g. tensile elongation of 20% or greater in a 2 in. (50mm) gauge length; (3) good weldability. (p. 9.1-161).

It is believed this confidence in the stress-strain characteristics of steels manufactured to these standards and specifications is based on historic test data for such steels manufactured in the US. The wide flange shape specification ASTM A992/A992M (ASTM, 2015) includes a requirement to limit the maximum actual f_y/f_u ratio and yield strength of the steel, see Table C1.

It should be noted that in the US seismic connections are designed in accordance with AISC Seismic Provisions and AISC 358 Prequalified Connections (AISC, 2016a) and welded to AWS D1.8 (AWS, 2016). This standards framework is more prescriptive as compared with NZS 3404, AS/NZS 5131 and AS/NZS 1554.1 in terms of fabrication details such as weld access holes, weld tabs and backing bars, demand critical welds etc. It is also more robust in terms of qualification of welding procedures, weld inspection and execution requirements. Prescriptive welding and fabrication requirements aim at reducing stress concentration effect in critical connections lowering the risk of brittle fracture. It appears to be an inverse relation between less conservative requirements for the notch toughness of steel and more prescriptive fabrication requirements as compared to New Zealand and European standards.

Canadian practice is similar to that of the US. The only additional requirement in CSA S16 (CSA, 2019) is the specification of an upper limit on the f_y/f_u ratio determined from minimum yield and tensile strength values in the steel standard.

Table C1

The Mechanical Properties of ASTM A992A/A992M Steels Relevant to Seismic Performance

Specification	Grade	Minimum % elongation at fracture	Maximum yield to tensile strength ratio	Maximum actual yield strength, f_y	Minimum Charpy V-notch energy
ASTM A992/A992M	50 ksi (345 MPa)	18% (200mm gauge length)[1] 21% (50mm gauge length)[1]	0.85[2]	65 ksi (448 MPa)	-

Notes.

1. The elongation at fracture limits are not directly comparable to those specified in AS/NZS steel standards as ASTM standards do not use proportional gauge lengths for computing elongation at fracture values
2. Based on the mechanical properties reported on a material test certificate

Japan
It is difficult to establish the Japanese material selection for seismic application criteria due to a lack of documents written in English. To some extent, Japanese requirements can be inferred from the technical publications of Japanese researchers and engineers written in English. It appears that the Japanese ductility criteria include low f_y/f_u limits, maximum actual yield and tensile strength, minimum elongation at fracture, and high impact toughness requirements for welded steel structures subject to high ductility demand. The Japanese structural steel standard, JIS G 3136 (JIS, 2012) has enhanced material properties for seismic applications. The key mechanical properties of steels manufactured to this standard are presented in Table C2.

Table C2

The Mechanical Properties of JIS G 3136 Steels Relevant to Seismic Performance

Specification	Grade	Minimum % elongation at fracture	Maximum f_y/f_u	Yield strength, f_y (MPa)	Tensile strength, f_u (MPa)	Minimum Charpy V-notch energy
JIS G 3136	SN400[1]	18-24[2]	0.80[3]	235 (min); 355 (max.)	400 (min.); 510 (max.)	SN 400B: 27J@0ºC
	SN 490[1]	17-23[2]	0.8[3]	325 (min.); 445 (max.)	490 (min); 610 (max)	SN 490B: 27J@0ºC

Notes.
1. Japanese grade designations are based on tensile strength.
2. Elongation at fracture limits vary according to material thickness.
3. Yield/ tensile strength ratio limit is based on steel test data.

China
The Chinese seismic design code (GB 50011, 2010) specifies limits on key ductility parameters, see Table 2. In addition to the material selection criteria, GB 50011 also recognises conforming steel grades with minimum Charpy V-notch impact properties. The conforming steel grades include Q235 B, C, & D and Q 345 B, C, & D. The key mechanical properties of steels manufactured to these grades are presented in Table C3.

Table C3

Mechanical Properties of GB/T 1591 Steels Relevant to Seismic Performance

Specification	Grade	Minimum % elongation at fracture	Maximum yield to tensile strength ratio	Maximum actual yield strength	Minimum Charpy V-notch energy
GB/T 1591	Q235-B, C, D	26 (t≤40mm)	0.64[1]	-	Sub-grade B: 27J @ 20ºC Sub-grade C: 27J @ 0ºC Sub-grade D: 27J @ -20ºC
	Q345-B, C, D	20 (t≤40mm)	0.73[1]	-	Sub-grade B: 27J @ 20ºC Sub-grade C: 27J @ 0ºC Sub-grade D: 27J @ -20ºC

Note. The yield to tensile strength ratio is based on the grade minimum values specified in GB/T 1591 (State Market Regulatory Administration; Standardization Administration of China, 2018).

Europe
The European seismic design code, Eurocode 8 (CEN, 2004), references the material requirements in the steel design standard, EN1993-1-1 (CEN, 2005a). Consequently, there is no differentiation of material ductility and impact toughness requirements for seismic and non-seismic applications. The ductility requirements from EN1993-1-1 have been reproduced in Table 2.

A conforming steel approach is used to select product that complies with the EN 1993-1-1 ductility requirements. The steel grades referenced in this standard are accepted as satisfying these requirements even though the steel maker is not required to check all these ductility requirements as part of their routine product inspection and testing regime. The mechanical properties of a selection of referenced steels grades are presented in Table C4.

Table C4

Mechanical Properties of EN 10025 Steels Relevant to Seismic Performance

Specification	Grade	Minimum elongation at fracture %	f_y/f_u	Tensile strength, f_u (MPa)	Minimum Charpy V-Notch Impact Energy
EN 10025	S275	23 (t≤40mm)	0.64[1]	410 (min) 560 (max)	JR 27 J @ 20ºC J0 27 J @ 0ºC J2 27J @ -20ºC
	S355	22 (t≤40mm)	0.7[1]	470 (min) 630 (max)	JR 27 J @ 20ºC J0 27 J @ 0ºC J2 27J @ -20ºC K2 40 J @ -20ºC

Note. The yield to tensile strength ratio is based on the grade minimum values from EN 10025-2 for steel thickness 16mm or less. From "Hot Rolled Products for Structural Steels: Part 2: Technical Delivery Conditions for Non-Alloy Structural Steels," by CEN*,* 2005*,* Copyright 2005 by European Committee for Standardization.

Material selection to avoid brittle fracture is undertaken in accordance with EN 1993-1-10 (CEN, 2005b). A point to note is that the selection procedure in this document does not incorporate some of the key elements of seismic loading, namely a high strain rate and plastification of the section. All steels produced to the steel standards referenced in EN 1993-1-1 must have minimum guaranteed impact properties, the requirements for subgrades JR, J0, J2, and K2 are noted in table C4. The steel maker is not required to routinely undertake Charpy V-notch testing for subgrade JR and J0 steels.