

Section A

INTRODUCTION AND PHILOSOPHY

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This paper is the result of deliberations of the Society's Study Group for the Seismic Design of STEEL STRUCTURES.

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2. INTRODUCTION

Over the past 10-15 years significant progress has been made in New Zealand and overseas in the design and construction of buildings, bridges and other structures for earthquake resistance. The principal developments have been in better understanding of the performance of structural materials and elements subjected to cyclic loading; improved analysis and design; greater attention to detailing of elements and the application of more rigorous quality assurance procedures to design and construction. The contribution to these developments made by the New Zealand Universities, research organisations and designers has been well documented in the pages of this Bulletin and elsewhere. Construction in reinforced concrete has benefitted greatly from this progress particularly in New Zealand. For a number of reasons, many of which are outside the influence of designers, the design of steel structures for earthquake resistance has not made the same progress.

By comparison the seismic performance of reinforced concrete elements and structures is much more complex, particularly in the case of elements subject to moment and shear. As a result of the challenge, over the past decade there has been a

rigorous programme of research including analysis, design and testing to try and clarify the problem. This research effort has helped significantly in a better understanding of the capacity and performance of reinforced concrete elements and structures. This has also extended to concrete masonry.

A comparable effort has not been made in the case of structural steel with the result that the analysis and design of steel structures for earthquake resistance has not made the same overall progress.

The current code for the design of steel structures NZS 3404 was produced in 1976 in an effort to assist designers in structural steel to meet the 'ductility', 'capacity design' and 'concurrent effects' considerations required by the loadings code NZS 4203. It was regarded as an interim design code which would subsequently be replaced by a more detailed code following the introduction of limit states or load and resistance factor design procedures to replace permissible stress design rules. Progress in the production and adoption of limit state codes overseas has been slow while the input required to produce such a code for New Zealand conditions including seismic requirements, was considered beyond the resources available.

As a result, it is widely recognised that in many areas, an urgent updating of the basis for the design of steel structures for earthquake resistance is required. The urgency is further accentuated by the increase in steel construction, involved in the industrial complexes required in New Zealand in the next decade, to process natural resources.

In addition, there have been a number of developments in steel structural systems, such as eccentric and bent bracing, and steel shear walls, which are beyond the scope of NZS 3404 and also NZS 4203.

Following the success of previous study groups, which covered reinforced concrete frames, reinforced concrete shear walls and bridges, the Management Committee of the New Zealand National Society for Earthquake Engineering set up a study group of engineers to consider the state of the art in the design and construction of steel structures. Financial and other support for the project was received from the New Zealand Heavy Engineering Research Association.

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The objectives of the project are:

- a. To update seismic design and construction procedures in structural steel to meet generally accepted requirements and those likely to arise in the next decade in New Zealand. Particular attention has been given to heavy industrial construction in steel, relevant to petrochemical and other resource oriented projects of the future.
- b. To identify important problem areas that should be researched in New Zealand.
- c. To adopt or adapt overseas developments and procedures in steel design and construction for New Zealand conditions.
- d. To compile and publish a set of recommendations covering the design and construction of steel structures for earthquake resistance.
- e. To identify and make available information on areas of engineering design in structural steel where the existing building code requirements, and particularly NZS 3404, are inadequate or do not even exist.

3. PERSONNEL

The study group at the present time consists of the following members:

Messrs. K.C.F. Spring	Chairman -		
	Consulting Engineer		
R.A.J. Cook	Secretary -		
	Ministry of Works		
	and Development		
G.R. McKay	Ministry of Works		
	and Development		
Dr. W.R. Walpole	University of		
	Canterbury		
Dr. J.N. Butterworth	University of		
	Auckland		
Messrs. G.C. Clifton	HERA		
G.W. Butcher	Consulting Engineer		
	(replaced		
	D.N. Undrill)		
C.J.A. Nicholas	"	"	
R.N. Patton	"	"	
Dr. A.M. Reay	"	"	
G.K. Sidwell	"	"	

Overseas Corresponding Members:

Dr. J.M. Rotter	University of Sydney
Professor Ben Kato	University of Tokyo
Professor K. Takanashi	University of Tokyo

The study group met together on 13 occasions to discuss and reach consensus in papers produced by members or regional groups.

4. PAPERS

The results of the deliberations of the study group are set out in the following papers:

<u>PAPER</u>	<u>TITLE</u>	<u>AUTHOR</u>
A	Introduction and	K.C.F. Spring G.W. Butcher
B	Analysis and Design Methods	R.N. Patton
C	Beam Design	W.R. Walpole G.W. Butcher
D	Column Design	J.W. Butterworth K.C.F. Spring
E	Concentrically Braced Frames	W.R. Walpole
F	Eccentrically Braced Frames	G.K. Sidwell
G	Connection Design	C.J.A. Nicholas
H	Beam-Column Joints	W.R. Walpole
I	Composite Design	G.C. Clifton
J	Cold Formed Sections	G.C. Clifton
K	Materials and Workmanship	G.R. McKay

5. SEISMIC DESIGN IN STRUCTURAL STEEL

Since its early introduction as a building form, engineers have been aware of the inherent ductility of steel as a material.

It is important to recognise the difference between the terms ductility applying to a structural material, ductility factor applying to an element and the overall ductility factor required for a structure.

Ductile behaviour is critical in structures which yield in a severe earthquake "to enable a structure to survive without collapse" [13].

Ductility factors for steel elements vary for tension, bending, shear and compression [14]. The highest being tension, which equates the material ductility and the lowest, compression. To achieve adequate ductility factors in direct compression, compression in bending and also in shear, it is necessary to take precautions to avoid local and/or lateral buckling.

Ductility factors for steel are generally higher than for reinforced concrete and this was acknowledged in the first publication of the loading code NZS 4203, with the adoption of a lower value for 'M' than other materials. With the publication of NZS 4203:1984 however this material advantage has been eliminated with a similar value now being assigned to reinforced concrete.

From the viewpoint of strength, the performance of steel buildings and structures subjected to strong earthquakes has been good. However collapses have occurred, the most recent and most spectacular being that of the 20 storey Pinot Saurez tower in the September 1985 Mexican earthquake. The use of structural

steel will not, in itself, overcome problems of poor design and poor workmanship, and so ensure good seismic performance.

As with other structural materials, measures must be taken to ensure that brittle failure does not occur in elements in the inelastic range. Such measures include the selection of steels with good yield and strain-hardening characteristics; providing restraints to prevent lateral buckling; controlling width to thickness ratios of members to delay the onset of severe local buckling and the adoption of quality assurance procedures to eliminate significant fabrication defects.

Providing reasonable precautions are taken, the behaviour of structural steel elements and structures in the inelastic range is both excellent and predictable. The predictable behaviour is exemplified by stable hysteresis loops and little or no deterioration in stiffness and strength.

When the Structural Steel Code NZS 3404 was published in 1976, many of the rules adopted to prevent brittle failure were those developed previously for plastic design. These rules were the result of research in analysis and design techniques in the post World War II years for the plastic design of structures. The rules were based upon monotonic loading and aimed at developing sufficient inelastic capacity to provide moment redistribution and to produce a chosen mechanism. The influence of cyclic loading and low cycle fatigue has since been investigated by a number of US and Japanese researchers and have supplemented the plastic design criterion.

Recent testing by Whittaker at the University of Canterbury [10] has indicated that the local buckling (b/t) rules for plastic design need to be revised to ensure good inelastic cyclic performance. This is discussed in more detail in Papers C and D and recommended rules are provided.

6. STRUCTURAL SYSTEMS

The following framing systems and the elements that comprise them are discussed in later papers:

These are:

- a) Moment Resisting Frames
- b) Centrally Braced Frames
- c) Eccentrically Braced Frames

Additionally, the following structural systems, although not reported in the papers prepared by the group, have been used successfully for seismic design of structures. These are:

- d) Steel Shear Walls
- e) Bent Bracing Frames
- f) Energy Absorbing Elements in Braced Structures
- g) Base Isolation
- h) Holding Down Bolts.

a) Moment Resisting Frames

As a building form, such frames provide the greatest degree of planning flexibility. In addition moment resisting frames in structural steel are extremely ductile because of their ability to absorb and dissipate energy without a loss of strength. This ability depends upon a sensible philosophy, e.g. weak beams, strong column.

The joints between beam and columns can readily be made by either:

- ... Fully Welding
- ... Welding the flanges and bolting the webs
- ... Bolting both the flange and webs.

An inherent disadvantage with moment resisting frames in structural steel is that stiffness will often dictate sizes. Also, in order to achieve full ductility, sizes greater than those required for strength alone, will often be required.

Hjelmstad and Popov [15] have generalised the concept of framing systems and show the relationships between stiffness, column size and shear deformation parameters for variation e/L ratios, aspect ratios and element stiffness ratios.

b) Centrally Braced Frames

Are an excellent structural form where the ductility demand is not high and full flexibility of building area is not required.

With the stiffness of such frames separation of secondary elements is not onerous. However, should the ductility demand be high, care must be taken to ensure that the ultimate strength of the structure can be attained.

Bracing for such frames have shown a marked tendency to degrade under cyclic loading and as a consequence the seismic performance of braced frames has been variable.

Minor structures using tension braces have often performed badly due to poor detailing and the absence of a capacity design approach.

On the other hand, major braced structures have usually performed well due to the care taken in detailing such structures.

c) Eccentrically Braced Frames

This form of structure has exhibited many of the advantages of the two previously mentioned. Stiffness, to limit drift, under wind or moderate earthquake attack is high, while the shear links that are characteristic of such frames have exhibited a high degree of ductility during cyclic testing, i.e. the ability to absorb and dissipate energy without loss of strength. Bracing systems of this type have many uses in industrial type structures.

An apparent disadvantage in buildings is the lack of flexibility when planning floor areas. Another is that under high seismic attack, the shear links develop marked deformations due to the fact that energy dissipation is localised. This could result in significant building repairs after an earthquake, particularly to floor slabs.

Eccentrically braced frames can be framed in a number of ways with the shear link at one or both ends of a beam or in the centre of the beams.

Eccentrically braced frames have similar energy dissipation characteristics to moment resisting frames.

d) Steel Plate Shear Walls

In recent years steel plate shear walls have been used in new high rise commercial buildings [2], hospitals [3] and in the strengthening of existing buildings [4].

In all cases the design appears to have been carried out on an elastic basis. At this time, little work has been done on the effects of cyclic loading and the requirements for ductile behaviour.

For bare steel shear walls an obvious analogy is with that of plate girders. Kulak [5] et al have shown that the considerable post buckling strength that is present in the web of plate girders due to tension field action, can be translated to bare steel plate shear walls.

Additionally, in the paper by Kulak [5] acknowledgement is made of the effect of columns as flanges. This is not ignored as happens with plate girders.

For composite steel/concrete shear walls, the approach by Canon and Dean [3] was to consider the shear buckling strength of the plate and to provide concrete cover such that out of plane panel buckling was prevented.

Where steel shear walls are used to strengthen existing buildings and are fixed to concrete columns, then tension field action should not be relied upon as such a mode is associated with large displacements. For these designs accepted methods to define shear and compressive buckling would be more appropriate.

From our findings a considerable amount of work is still required before a design approach using other than $S = 6$ could be contemplated.

e) Steel Bent Bracing

Bent bracing as the terminology suggests has an initial deflection provided at the centre. Work to date has limited the q value, i.e. e/L to 0.06 and limitations have been placed on slenderness ratios. The maximum ratio to preclude out of plane buckling being 140.

As far as is known bent bracing has not yet been used in buildings. However, studies carried out at the Kajima Institute of Construction Technology [1] have shown that such structural systems exhibit large ductilities.

f) Energy Absorbing Elements in Braced Structures

Preliminary tests [6] have been carried out on energy absorbing devices fixed to diagonal braces at their intersection. The initial tests were confined to circular and square devices made from reinforcing rods. From these preliminary tests it was shown that the square device had the better energy absorption capacity.

It is the intention of the DSIR to carry out further work encompassing both theoretical analysis and laboratory testing of rectangular elements of varying geometry.

From this programme it is hoped that simple design procedures can be developed so that practising engineers have the means of incorporating them in typical structures.

g) Base Isolation

Techniques for the design of tapered steel energy dissipations have been developed to allow the base isolation of structures [7]. The types used were of a tapered form and either round or rectangular in section.

The theory developed and subsequent testing showed that such devices have a predictable performance and are capable of absorbing further energy as strains increase until failure is reached.

h) Holding Down Bolts

In many structures to compute the collapse load it is necessary to have plastic hinges form at the base.

To ensure a ductile response, yielding of the holding down bolts may be required. Previous work by R. Shepherd [8] and A.H. Bryant and S.S. Powell [9] have developed design procedures to ensure that yielding does take place. The design detailing for such a system is to have upset threads on the bolts, in lieu of cut thread which have the strong possibility of incurring brittle failure.

7. FUTURE RESEARCH

A significant amount of research is still required for the seismic design of structural steel.

Problem areas that still require further verification are:

- a) Local buckling criteria for varying S values and structural systems. Recent work by Walpole and Butcher [16] has thrown into question the plastic design values of the AISC adopted by Popov [11] and others.

- b) The lateral torsional buckling rules applying to plastic design also require research.
- c) The ability of uncritically loaded columns under cyclic loading to provide overall frame stability where one column may have reached or exceeded its critical load. The existing work of Yura [12] on this topic has only examined the case of gravity loads.
- d) The development of ductile composite frames and the design criteria for such elements.
- e) The investigation of steel shear walls under cyclic loading and the development of design criteria.
- f) The evaluation of buckling lengths for columns under cyclic loading and the rotational restraints provided by beams yielding at each end of the member.
- g) The formulation of rules to cover higher mode effects and biaxial bending. Also the applicability of rules applying to reinforced concrete need to be investigated.
- h) The formulation of a New Zealand steel structures code in limit state format including seismic provisions.

8. CONCLUSIONS

The seismic design of structural steel in all its varying forms is now a complex matter which is not well covered in the existing steel structures code NZS 3404 nor in overseas codes.

Many of the assumptions made by the Group still require verification and it is anticipated that the Universities of this country will take up the challenge. While the Group does not have official SANZ backing it is hoped that many of the anomalies now existing in NZS 3404 and highlighted by the Group, will be corrected when this code is revised. Additionally we would anticipate that the proposed rules for ductile and low ductility demand will be incorporated in a revised NZS 3404.

The Group has taken a long time to reach its conclusions and in doing so we believe has highlighted the lack of current knowledge on seismic design in structural steel. However tentative rules have been formulated in the various papers for the classification and design of individual elements depending on whether they are:

- .. fully ductile
- .. have limited ductility
- .. remain elastic

The problem has been exacerbated with the uniqueness of NZS 4203, its requirements for capacity design and ductile behaviour and the lack of precedent in overseas codes. However, we believe structural steel to be

a viable and logical alternative to other materials in the seismic design of structures. The acceptance of the challenge of Section 7 will help to give greater confidence in the ability of structural steel to perform well in earthquake resistant structures.

We would like to express our gratitude to the Management Committee of the Society for the indulgence shown to the Group in the time it has taken to research and publish the papers, and also to the Heavy Engineering Research Association for its cooperation and necessary funding of the Society.

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