Steel Innovations Conference 2015
Auckland, New Zealand
3-4 September 2015

ANALYSIS OF THE SUSTAINABILITY CREDENTIALS OF HIGHER STRENGTH STRUCTURAL STEEL COMPRESSION MEMBERS

A. Ng[1] and A. Syam[2]

ABSTRACT

Apart from the obvious structural efficiencies, the use of higher strength steels also has the potential to improve the sustainability credentials of a structure as it is able to reduce the amount of resources used without impacting on its function. If we consider that a sustainable development is one that meets the needs of the present without compromising the ability of future generations to meet their own needs, then the waste hierarchy of Reduce, Reuse and then Recycle is fundamental to sustainability. That is, if designers reduce the amount of resources they use, it is better than both reusing and recycling. Intuitively structural steel members in compression can be reduced in size if their yield strengths are increased because they are designed generally on the basis of strength rather than deflection.

This paper provides quantitative analyses of the material savings as a result of using a higher strength grade of steel in a building structure. The columns of multi-storey buildings, 350 MPa versus 300 MPa and 400 MPa versus 300 MPa are examined to determine the range of material savings that can be achieved using a higher grade of steel.

The Green Building Council of Australia in their 2010 Green Star tool and, again with the release of their 2014 Design and As Built Green Star tool, recognise the benefits of using higher strength grades of steel. This was initially based on a study of possible material savings on the design of individual members in the standard grade and the higher grade for both hot-rolled and welded steel sections. This study confirms that material reductions are achievable in the members of actual structures built in the field.

[1]Engineering Solutions Manager, OneSteel
[2] Industry & Trade Development Manager, Austube Mills.

Introduction

This paper proposes that environmental sustainability is generally enhanced by using higher grades of steel. The first section of the paper explores the sustainability benefits of reducing steel usage, while the second section of the paper demonstrates the material savings achieved by utilising higher grades of steel. Building elements in compression are analysed to quantify the savings by utilising a higher grade of steel.

The sustainability benefits of reducing the amount of steel used in a building over recycling can be determined by comparing the raw material usage and the waste products generated by the two alternatives. It is no surprise that the results are in line with the waste hierarchy that dictates that reduction is better than reuse which is in turn is better than recycling.

Higher grades of steel will result in lower quantities consumed generally whenever serviceability criteria are not critical. The authors of this paper present the findings of a study to determine the potential savings in material usage for compression members. The members examined are universal column and welded column sections acting as columns. It follows the research by Ng, Yum and Bell (2010) which compared the use of 300 MPa and 350 MPa grades of steel in composite floor beams which were found to governed by strength design and not serviceability. The higher strength steel, in that case, produced an average of 8% saving in steel across the entire floor.

Sustainability

Green Building Councils

The sustainability credentials of a building is commonly measured by a Green Star system produced by a member of the World Green Building Council. In Australia it is the Green Building Council of Australia's (GBCA) Green Star rating tool that is predominately used, while in New Zealand it is the New Zealand Green Building Council's (NZGBC) Green Star rating tool that dominates. While there is close relationship between the GBCA and the NZGBC and indeed a good alignment in their respective Green Star rating tools, there is currently a significant difference in the way they rate the environmental sustainability of steel as a construction material.

Before May 2010, both Green Building Councils rewarded recycled steel content for its perceived sustainability credentials. However, after the GBCA's review of the steel credit in its Green Star tool, it recognised that rewarding recycled content was not improving the overall sustainability in building construction. The GBCA's Steel Expert Review Panel (SERP) found that the Australian steel industry was already recycling approximately 90% of available construction, demolition and industrial (CD&I) scrap steel (Hyder, 2009). Thus steel credit points rewarding recycled content was unlikely to impact significantly on improving the recycling rates for CD&I scrap. It is reasonable to assume that the recycling rates in New Zealand are comparable given that it is the high economic value of scrap steel that drives the recycling rate and not Green Star Rating tools.

The GBCA in 2010 moved away from rewarding recycled content in steel to rewarding reduced usage of steel and the NZGBC appear to be now moving in the same direction. In the GBCA's 2010 Green Star Green Star rating tool it rewarded the use of higher grades steels on the basis that this generally led to reduced material usage and was a simple, readily measurable quantity. More recently, in 2014 the GBCA recognised that sustainability practitioners were producing building models which made the comparison of building material usage relatively routine and so offered, as an alternative to the use of higher grades, the option to quantify the reduction in steel used compared with a standard building. To date the NZGBC are still rewarding recycled content, however this may be changing. In the Materials Category Review draft that the NZGBC published for feedback in May 2015 the proposed Steel Material Credits does not reward recycled content. However, it is still lagging behind Australia in recognising the sustainability benefits of reducing the amount of steel used in a project.

Reduce, Reuse, Recycle

It is important to understand why reducing the amount of steel used is a more effective driver of sustainability than recycled content if we are to promote change for the better in the NZGBC Green Star rating tool. The GBCA's SERP achieved this by drawing upon the sustainability fundamentals and considering the waste hierarchy of Reduce, Reuse then Recycle. They concluded that recycling steel is significant in improving the sustainability of construction projects through lower emissions, depletion of raw materials, air pollution, destruction of habitats etc. (Norgate, 2004, Dept of Environment and Conservation (NSW) (2005), Strezov and Herbertson, 2006, Gaballah and Kanari, 2001), however, consideration to reducing the amount of steel used in construction or reusing deconstructed steel members in construction should take priority in the design and specification of building projects.

Calculations to provide an indication of the relative sustainability “value” of Reduce vs Reuse vs Recycle were undertaken by members of the SERP. The typical savings in raw material and energy and the reductions in waste products were compared to the benchmark of steel produced using an integrated blast furnace process or basic oxygen furnace (BOF). Table 1 gives the raw materials and energy to produce a tonne of steel using the BOF and Electric Arc Furnace (EAF) production processes, while Table 2 gives a comparison of waste products produced again using each of the BOF and EAF processes (Strezov, L and Herbertson, J, 2006).

Table 1: Raw materials inventory & Energy per tonne of steel

Inventory	**Virgin Steels (BOF)**	**Recycled Steels (EAF)**
Coal (t)	0.84	0.57
Iron Ore (t)	1.35	0.10
Limestone (t)	0.34	0.14
Natural Gas (GJ)	4.73	2.01
Crude Oil (GJ)	1.40	0.31
Fresh water (m^3)	2.82	1.29
Energy (GJ)	25.5	12.1

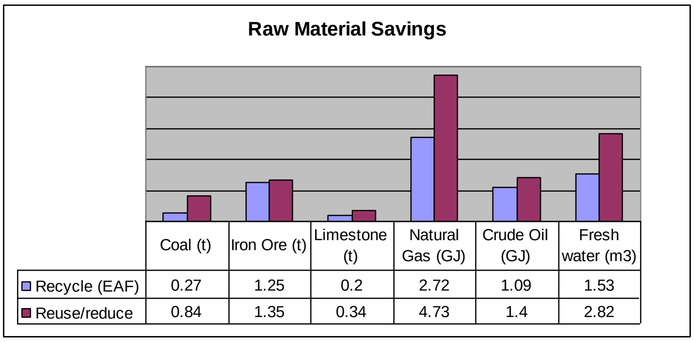


Figure 1 – Raw material savings/tonne of steel

Table 2: Waste products per tonne of steel

Waste Products	**Virgin Steels (BOF)**	**Recycled Steels (EAF)**
GGE (t CO_2-e)	2.35	1.12
NO_X (kg)	2.83	0.44
SO_X (kg)	0.45	0.18
Solid Waste (t)	0.15	0.12
Stored Slag (t)	0.35	0.05

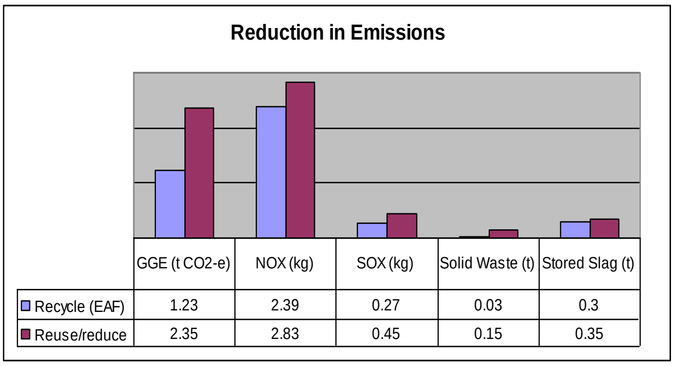


Figure 2 – Reduction in emissions/tonne of steel

For every tonne of steel that is reduced in use on a project the savings in raw material or reduction in waste products will be equivalent to the values in each of the tables under virgin steels (BOF). The same savings are available if steel is disassembled from another building that has reached the end of its useful life and reused on another project because again it is steel that is not used. It follows that the savings in raw materials and reductions in emissions from using EAF steels is the difference in value between the BOF and EAF steels. A comparison of these savings is presented in Figures 1, 2 and 3. The reduction in raw materials is most significant for coal, limestone, natural gas and fresh water. Savings in energy are more than doubled. Increases in emission reductions are equally significant, particularly in the categories of solid waste and green-house gas emissions.

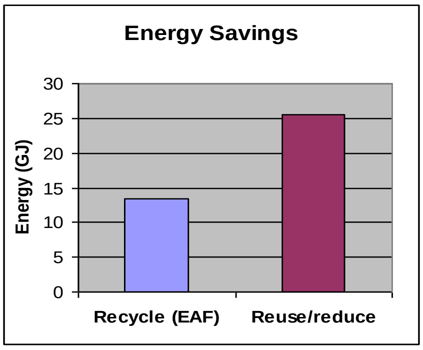


Figure 3 - Energy saving/tonne of steel

It is clear from the analysis of the preceding data that a reduction by one tonne of steel used on a project has greater sustainability benefits than using a tonne of recycled steel. For steel to be recycled from CD&I, a building must be demolished and the steel components sent to scrap rather than to the more sustainable option of member reuse, which should be encouraged over recycling as this produces the same savings as reducing in comparison with recycling. Furthermore, greater sustainability is achieved by encouraging the reuse of a building rather than to demolish or deconstruct, which consumes additional resources, confirming reduce at the top of the hierarchy.

Higher strength steel reduce material usage

Previous studies

The SERP proposed the use of higher strength steels to drive a reduction in steel usage based on:
1) Historical data when the standard grade of steel in Australia was moved from 250 MPa to 300 MPa
2) A rudimentary comparison of the design capacity of individual steel members in standard grade and the higher grade for both hot-rolled and welded sections.
3) A comparison for the composite steel floor beams in a typical steel frame structure constructed in Sydney.

A rudimentary study using tabulated design capacity values of standard grade of steel compared with the higher grades for individual members demonstrates potential material savings. This study supports the data that, the move from 250 grade steels to 300 grade steels for hot rolled structural sections in Australia during the mid-nineties, saw a reduction in the quantities of steel used due to the additional strength of the members. However, there was a concern amongst some of the SERP members that deflection controlled structural designs in 300 grade members and that using a higher grade would not reduce steel quantities in the design. This view was investigated by examining the design of an office building using OneSteel 300PLUS® sections compared with OneSteel 350 grade sections.

Though many structural engineers would have intuitively thought that deflection would limit most of the potential savings, it was not the case. Ng, Yum and Bell (2010) found that the web penetrations required to cater for the air handling services dictated that strength was generally more critical than serviceability. The columns in the same building are the subject of this paper which examines the possible savings for compression members. The expectation is that elastic deformation of a column by axial shortening is expected to be less significant than the elastic deformation of a beam by deflection, therefore the material saving produced using a higher strength steel will be greater for columns than for beams.

Columns designed using higher strength steels

Office Building

The four storey office building with basement carpark (refer Figure 4) which has been built in Sydney that was the subject of the study by Ng, Yum and Bell (2010) was again utilised in this study for consistency. The use of this building also ensures that the layouts and loadings continue to be representative of contemporary office buildings. The grid spacing is as shown in Figure 4 with four identical office levels with a floor to floor height for each level of 4.0 m. A basement carpark is located below the building and a concrete roof caps the top of the building. The concrete filled tubes on grids 1 and 8 were not included in this study.

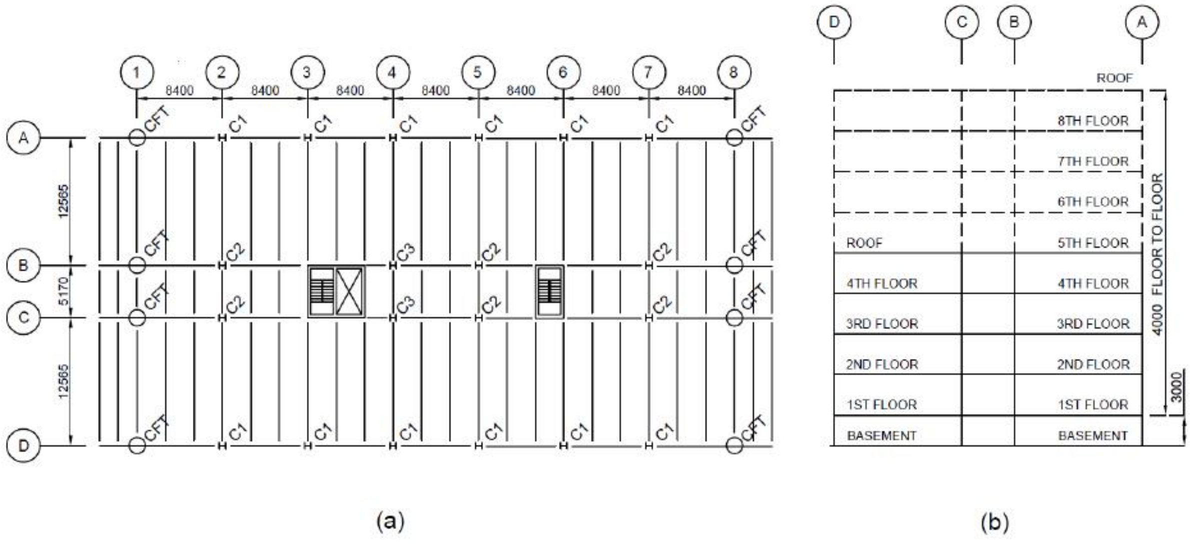


Figure 4: (a) Plan on level 2 showing column layout
(b) Elevation showing floor to floor heights for four storey and eight storey option (dotted)

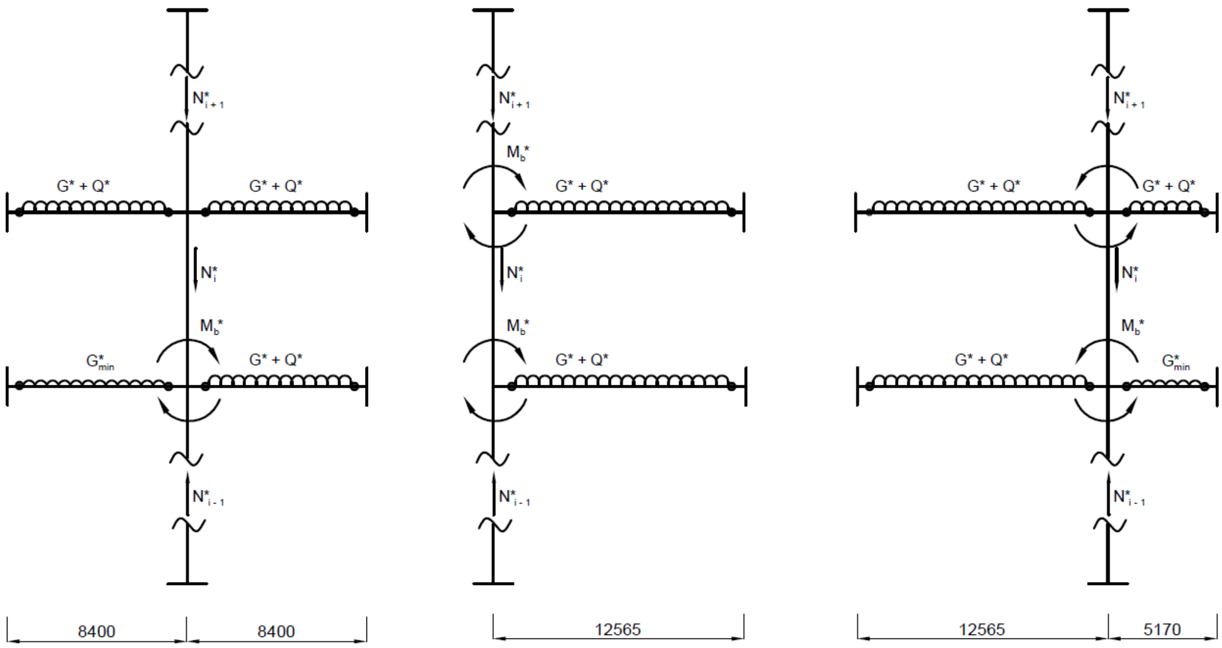
The grids are typically 12.5 m x 8.4 m providing approximately 1950 m^2 per floor, live loading for the general office areas was 3 kPa with a superimposed dead load (SDL) of 1.5 kPa, while the concrete roof has a design live load of 2.0 kPa. The edge beams carry a façade load allowance of 2.0 kN/m.

The study also considered the potential material savings for a “short” column compared to a “long” column when a higher grade of steel is used. For a short column the Steel Structures Standards (AS 4100 and NZS 3404) deem that the member capacity is equal to the axial capacity which is directly proportional to the grade of the steel. Thus the 16% increase from 300 MPa to 350 MPa for a short column results in a 16% material saving. For a long column the member capacity is equal to the axial capacity multiplied by a slenderness reduction factor which subsequently reduces the 16% material savings offered by the higher grade of steel. To examine the impact of short columns over long columns an eight storey building with the same foot print and floor to floor height was investigated (refer Figure 4). Even though the floor to floor heights of each of the eight levels are the same the relative shortness of each column increases down the building due to the smaller slenderness reduction factors of the larger columns that are required to carry the cumulative loads from each floor above.

The Design

The building and its elements were analysed and designed in accordance with the Steel Structures Standards (AS 4100 and NZS 3404) adopting the simple construction category. The lateral stability of the building is provided by the concrete cores within the building, so the steel columns were not required to carry any racking loads.

The design parameters adopted for the columns were based on the Steel Structures Standards and what is generally accepted practise by Structural Engineers. A live load reduction was applied in accordance with AS/NZS 1170.1 to the column wherever it was applicable, while full pattern loading of the live load and superimposed dead load was considered to provide the most adverse loading conditions for bending and compression. Figure 5 shows the pattern loading adopted. In this project, and typically on most projects both primary and secondary beams are connected to columns by what is considered a simply supported connection. Consequently, the unbalanced moment on the column was determined by applying the beam reactions a nominal 100 mm from the face of the column.



(a) (b) (c)

Figure 5: Pattern loading for column design
(a) Equal span beams each side; (b) Edge Column; (c) Unequal span beams each side

The effective-lengths of the columns were conservatively considered to be in single curvature given that both primary and secondary beams are connected by simply supported (nominally pin) connections. For edge columns there is a case for considering the column being in double curvature from the eccentric beam reactions from each floor. However, where the compressive load is high there may be a tendency for columns to buckle in single curvature and thus dominate over the moment from the nominal eccentric load. Most designers take the more conservative approach of the column buckling in single curvature and this was the convention adopted in this study. In any case, the design parameters were the same for all grades of steel ensuring a like-for-like comparison.

Optimal design versus rationalised design

The first iteration in the column's design was to determine an appropriate section at each level. A spread sheet was used to generate and cumulate the axial loads taking into account the live load reductions and the moments from the eccentric loads of the simply supported beams at each level. CHECKSTEEL, a software program that designs steel members to AS4100 was used to generate acceptable sections for each load case. Table 3 shows the sections required at each level for the four storey office building and Table 4 shows the sections required at each level of the hypothetical eight storey office building.

Table 3: Column design sizes at each level of four storey building

Level	Length (m)	Column C1		Column C2		Column C3	
		300PLUS®	350 Grade	300PLUS®	350 Grade	300PLUS®	350 Grade
4	4	150UC37.2	150UC37.2	200UC46.2	200UC46.2	200UC46.2	200UC46.2
3	4	200UC59.3	200UC59.3	250UC72.9	250UC72.9	200UC59.3	200UC59.3
2	4	250UC72.9	250UC72.9	250UC89.4	250UC89.4	250UC72.9	250UC72.9
1	4	250UC89.5	**250UC72.9**	310UC96.8	310UC96.8	250UC72.9	250UC72.9
B	3	250UC89.5	250UC89.5	310UC118	**310UC96.8**	250UC72.9	250UC72.9
Total Weight (kg)		1304	1238	1575	1512	1224	1224

Table 4: Column design sizes at each level of eight storey building

Level	Length (m)	Column C1		Column C2		Column C3	
		300PLUS®	350 Grade	300PLUS®	350 Grade	300PLUS®	350 Grade
8	4	150UC37.2	150UC37.2	200UC46.2	200UC46.2	200UC46.2	200UC46.2
7	4	200UC59.3	200UC59.3	250UC72.9	250UC72.9	200UC59.3	200UC59.3
6	4	250UC72.9	250UC72.9	250UC89.4	250UC89.4	250UC72.9	250UC72.9
5	4	250UC89.5	**250UC72.9**	310UC96.8	310UC96.8	250UC72.9	250UC72.9
4	4	310UC96.8	**250UC89.5**	310UC137	**310UC118**	250UC89.5	250UC89.5
3	4	310UC118	**310UC96.8**	310UC158	**310UC137**	310UC96.8	**250UC89.5**
2	4	310UC137	**310UC118**	350WC197	**310UC137**	310UC96.8	310UC96.8
1	4	310UC137	**310UC118**	350WC197	**310UC158**	310UC118	**310UC96.8**
B	3	310UC158	**310UC118**	350WC197	**310UC158**	310UC118	**310UC96.8**
Total Weight (kg)		3465	3012	4568	3895	2964	2786

In the four storey building the number of instances where the higher strength steel reduces the sections size is limited to just 2 (shown in bold) out of the possible 15. It was expected that 4 metre columns carrying four office levels would result in relatively "long" columns rather than "short' columns which are less favourable for a size reduction from a higher strength steel. None-the-less it was surprising that only 2 columns benefitted from higher strength steels. This is in part can be explained by the finite number of sections available for design. More section sizes would have possibly produced different results.

The benefit that higher strength steels offer 'short' columns over 'long' columns is illustrated by the design sections for the eight storey building. 14 (shown in bold) out of the 27 columns sections are lighter due to the use of a higher strength steel. As the loads are higher, the columns are larger for the same effective length giving a shorter column. Tables 5 and 6 show that the higher grade of steel in the columns of the four-storey office building produces a total material savings of 4.2%, while the eight-storey office building produces a significantly higher saving of 13.4%.

Table 5 – Weight savings for a four storey building using higher grade steels

		Weight/Column (kg)		Total Weight (kg)		% Weight Saving
Col Mark	No.	300PLUS	350 Grade	300PLUS	350 Grade	
C1	12	1304	1238	15649	14852	5.1%
C2	10	1575	850	15752	15116	4.0%
C3	2	1224	1224	2448	2448	0.0%
Total				33849	32416	4.2%

Table 6 – Weight savings for a eight storey building using higher grade steels

		Weight/Column (kg)		Total Weight (kg)		% Weight Saving
Col Mark	No.	300PLUS	350 Grade	300PLUS	350 Grade	
C1	12	3465	3012	41578	36149	13.1%
C2	10	4568	3895	45682	38952	14.7%
C3	2	2964	2786	5927	5572	6.0%
Total				93187	80673	13.4%

Material savings in columns with a rationalised design

Generally, in practice the section size of a column is not changed at every level and so this needs to be considered if this comparison to reflect the actual savings in practice. The cost impost of splicing columns of differing sizes is generally greater than the cost of using a column that is slightly larger than required on that floor. Engineers are conditioned by their training and the market to produce, first of all the most economical design and everything else including sustainability second. Therefore it is not surprising that columns and indeed most structural elements are rationalised both before design takes place as well as after design. Pre design, columns that are similar are grouped and designed together. Post design they are rationalised for what is believed to be more practical construction. The rationalisation may also lead to other cost savings including; reducing the wastage from standard lengths, and less crane time because there are less column lifts.

In this comparison, the column design has been rationalised to include columns spanning two or three levels. In the four storey building the first three floors of the column can be cut from a 12 m standard length and the following 2 levels from a 9 m standard length. A similar rationale is adopted for the eight storey building with an initial three level column lift followed by two storey lifts.

A rationalisation of the column sections gives rise to a variety of results which are tabulated in Tables 7 and 8. In the four storey building the benefits of the higher strength steel for columns with mark C1 are completely lost in the rationalisation process while the benefits for columns with mark C2 are extended. In the eight storey building the benefits for columns with mark C1 and C3 are increased post rationalisation, while the weight reductions for column with mark C2 are diminished.

Table 7: Rationalised column sizes at each level of four storey building							
		Column C1		Column C2		Column C3	
Level	Length (m)	300PLUS®	350 Grade	300PLUS®	350 Grade	300PLUS®	350 Grade
3 & 4	8	200UC59.3	200UC59.3	250UC72.9	250UC72.9	200UC59.3	200UC59.3
1 & 2	8	250UC89.5	250UC89.5	310UC118	**310UC96.8**	250UC72.9	250UC72.9
B	3	250UC89.5	250UC89.5	310UC118	**310UC96.8**	250UC72.9	250UC72.9
Total Weight (kg)		1463	1463	2013	1780	1276	1276

Table 8: Rationalised column sizes at each level of four storey building							
		Column C1		Column C2		Column C3	
Level	Length (m)	300PLUS®	350 Grade	300PLUS®	350 Grade	300PLUS®	350 Grade
7 & 8	8	200UC59.3	200UC59.3	250UC72.9	250UC72.9	200UC59.3	200UC59.3
5 & 6	8	250UC89.5	**250UC72.9**	310UC96.8	310UC96.8	250UC72.9	250UC72.9
3 & 4	8	310UC118	**310UC96.8**	310UC158	**310UC137**	310UC96.8	**250UC89.5**
1 & 2	8	310UC158	**310UC137**	350WC197	350WC197	310UC118	**310UC96.8**
B	3	310UC158	**310UC137**	350WC197	350WC197	310UC118	**310UC96.8**
Total Weight (kg)		3876	3343	4789	4192	3130	2838

The material savings from higher grade steels

The use of higher strength steel for columns resulted in material saving for the columns in both the four storey building and the eight storey building. The four storey building saw around a 5.8% saving while the eight storey building was more than double this value at 12.9%. Table 9 shows design rationalisation increased the material savings due the use of higher strength steels for the four storey building, while Table 10 shows it decreased the savings for the eight storey building. An examination of the individual columns from the basement to the roof confirms rationalisation will result in both increases and decreases in the material saving from using higher strength steels.

Higher strength steel used in the columns of these multistorey office buildings, regardless of the impact of rationalisation result in savings in some cases of up to 12.9%.

Table 9 – Weight savings for a four storey building using higher grade steels with rationalised columns						
		Weight/Column (kg)		Total Weight (kg)		% Weight Saving
Col Mark	No.	300PLUS	350 Grade	300PLUS	350 Grade	
C1	12	1463	1463	17555	17555	0.0%
C2	10	2013	1780	20132	17800	11.6%
C3	2	1276	1276	2553	2553	0.0%
Total				40239	37907	5.8%

Table 10 – Weight savings for a eight storey building using higher grade steels with rationalised columns						
		Weight/Column (kg)		Total Weight (kg)		% Weight Saving
Col Mark	No.	300PLUS	350 Grade	300PLUS	350 Grade	
C1	12	3876	3343	46517	40116	13.8%
C2	10	4789	4192	47886	41916	12.5%
C3	2	3130	2838	6260	5677	9.3%
Total				100663	87709	12.9%

Further Investigation

Reinforcing steels

It is evident from this study that higher grades of steel offer benefits for sustainable design. It is therefore a natural extension to consider the benefits higher grade steel may offer in reinforced concrete applications where the tensile and compressive strength can be fully utilised.

Conclusions

Examination of the raw materials consumed, and waste products released in the production of steel for building construction, confirm the waste hierarchy of Reduce, Reuse then Recycle. Reduction offers immediate sustainability benefits in steel construction. The design examples demonstrate the potential material savings through the use of higher grade steels in compression members. While the savings will vary from one member to another and from building to building it is evident that it has the potential to deliver greater improvements in sustainability than recycled content.

This study supports the Green Building Council of Australia's changes in both their 2010 Green Star Tool and 2014 As Built Green Star Tool. These GBCA tools have had a logical progression from recycled content to dematerialisation. Dematerialisation in the GBCA 2010 Green Star tools initially came in the form of high strength steel content and is now progressing in the 2014 tool to measuring actual quantities saved. In time it is expected that the NZGBC Green Star tools will be aligned; at which time, New Zealand Engineers can play their part in delivering improved sustainability by design.

References

Australian Standard (AS 4100:1998) *Steel Structures,* Standards Australia, SAI Global, Sydney.

Australian Standard/NewZealand Standard (AS/NZS 1170.1: 2002) *Structural design actions – Part 1: Permanent, imposed and other actions,* Standards Australia, SAI Global, Sydney

Department of Environment and Conservation (NSW) 2005, "Benefits of Recycling, Sustainability Programs Division", Found at: www.environment.nsw.gov.au/warr/BenefitRecycling.htm, accessed January, 2009

Gaballah, I. & Kanari, N. 2001, 'Recycling policy in the European Union', *Journal of Metals*, November, Vol. 53, No. 11, pp. 24-27

Hyder 2009, 'One-Steel Recycling Waste ferrous metal in Australia Estimate of steel disposed to landfill', Hyder Consulting Pty Ltd

New Zealand Standard (NZS 3404:2009), *Steel Structures Standard*, Standards New Zealand, Wellington

Ng, A, Yum, G. and Bell 2010. "The impact of higher strength steel on sustainable design", Australasian Structural Engineering Conference, Sydney Aug 2010.

Norgate 2004, 'Metal Recycling: An Assessment Using Life Cycle Energy Consumption as a Sustainability Indicator', CSIRO.

Strezov, L and Herbertson, J. 2006, 'Life Cycle Perspectives on Steel Building Materials' The Crucible