Institution: Imperial College London

Unit of Assessment: 14-Civil and Construction Engineering

Title of case study: 7. Structural use of stainless steel

1. Summary of the impact

National and International design codes are the key vehicles for enabling structural engineering research to impact on practice. Recent years have seen substantial advancements in such codes for stainless steel structures, to which Imperial has made outstanding contributions [A-E]. Imperial research has led directly to improved structural design provisions, enabling more efficient structures, leading to cost savings [G], further promotion of the use of stainless steel in construction [A,H,I] and a reduction in the use of construction resources. The impact and reach of Imperial's research has not only been throughout the industry (producers [H], code writers [A] and practitioners [G,I]) but also global, with widespread influence on UK, European, North American and Asian practice [A].

2. Underpinning research

Research into the behaviour and design of stainless steel structures has been carried out at Imperial College over the last 12 years. The research has been led by Professor Leroy Gardner and involved Professor David Nethercot, Professor Ahmed Elghazouli, ten PhD students and numerous undergraduate and MSc project students. The primary focus of the research has been to develop an understanding of the behaviour of stainless steel as a structural material through experimentation and modelling and to generate design methods suitable for incorporation into international design codes. The research has been funded by EPSRC, the European Union and numerous industrial sponsors. Many of the published research papers have featured in the most highly cited articles list in top journals. The key underpinning research contributions may be summarised as follows:

- Rigorous experimentation has been undertaken since 2001, e.g. [1, 2], on a range of structural stainless steel grades and section types. Innovative testing techniques have been developed [1] and followed by others, and Imperial has made the most substantial contribution to the international database of structural performance data [F]. These data have been used to underpin the development of new design rules and methods [3-5] in international design codes and to determine their statistical reliability.
- A consistent approach to the nonlinear numerical modelling of stainless steel structural components [6] and connections has been established. Models have been validated against a substantial pool of physical test results, and numerical prediction of the key performance measures has been achieved with a high degree of accuracy. Comparisons with tests and subsequent parametric studies have enabled the development of universal expressions for modelling material stress–strain behaviour, enhanced strength corner properties, initial geometric imperfections (local and global) and residual stresses. Confidence in the sophistication and reliability of the developed numerical models has enabled further structural performance data to be generated and areas to be explored beyond those considered experimentally. Over the past eight years, the findings and proposals have been adopted by many other researchers around the world, as indicated for example by over 80 citations to [6].
- Development of design rules for many aspects of structural stainless steel design, including cross-section classification, member buckling, new section types (oval hollow sections), the capturing of cold-work strength enhancements during forming, new grades of material (lean duplex stainless steel) and connections. Furthermore, a new design philosophy for stainless steel structures that recognises the particular nature of the material stress-strain response, has been devised. This approach, termed the continuous strength method (CSM), is based initially on deformation rather than strength and represents a radical departure from current practice. The CSM was established at Imperial and has been the topic of two prize winning papers published in 2004 and 2008 [3,4] and numerous keynote addresses at International Conferences. The approach offers substantial increases in load carrying capacities (up to 25%) over existing design methods, is included in UK and North American design guidance for stainless steel (see [A,C and E]) and has been used in practice to achieve more efficient designs [G].

3. References to the research

* References that best indicate quality of underpinning research.

*[1] Gardner, L. and Nethercot, D. A. (2004) 'Experiments on stainless steel hollow sections - Part 1: Material and cross-sectional behaviour' *Journal of Constructional Steel Research* **60**(9) pp

1291-1318, doi:10.1016/j.jcsr.2003.11.006
This paper makes the largest single contribution to the pool of available test data on structural stainless steel cross-sections. Innovative testing methods were devised to test curved corner coupons and compressive properties. The results have been widely used by other researchers for the calibration of numerical models and verification of design guidance.

[2] Theofanous, M. and Gardner, L. (2009) 'Testing and numerical modelling of lean duplex stainless steel hollow section columns' *Engineering Structures* **31**(1) pp 3047-3058. doi:10.1016/j.engstruct.2009.08.004
This paper presents the first set of structural experiments on a new grade of stainless steel referred to as 'lean duplex', owing to its low nickel content. Nickel has a strong bearing on both the price and volatility of price of stainless steels. The new grade is approximately half the cost and twice the strength of traditional austenitic grades of stainless steel. Detailed material characterisation, element testing and numerical modelling were conducted to underpin design recommendations, which have now been incorporated in design codes.

[3] Gardner, L. and Nethercot, D. A. (2004) 'Structural stainless steel design: a new approach' *The Structural Engineer* **82**(21) pp 21-28. Available at
http://www.istructe.org/journal/volumes/volume-82-(published-in-2004)/issues/issue-21/articles/structural-stainless-steel-design-a-new-approach
This prize-winning paper (IStructE Henry Adams prize) describes a new approach to stainless steel structural design, devised by the authors. The new method requires no iteration, involves similar calculation effort to current methods, and offers improvements in design efficiency of over 20%.

*[4] Gardner, L. (2008). 'The Continuous Strength Method' *Proceedings of the Institution of Civil Engineers - Structures and Buildings*. **161**(3) pp 127-133. doi:10.1680/stbu.2008.161.3.127
This paper presents a conceptually new approach to the design of metallic structures, the continuous strength method (CSM). The method moves away from traditional cross-section classification, and determines structural resistance on the basis of a continuous relationship between slenderness and (inelastic) local buckling and a rational exploitation of strain hardening. By departing from the current stepwise treatment and allowing for strain hardening, the CSM has been shown to offer increases in member resistance of about 25% over current European Standards and a reduction in scatter of the prediction. This represents a significant enhancement in efficiency and provides considerable savings in construction resources [A7]. The author won an ICE journal prize (Palmer Prize, 2008) for this paper and has given several keynote and invited lectures on the topic.

*[5] Cruise, R. B. and Gardner, L. (2008) 'Strength enhancements induced during cold forming of stainless steel sections'. *Journal of Constructional Steel Research*. **64**(11) pp 1310-1316. doi:10.1016/j.jcsr.2008.04.014
Significant strength enhancements arise during the cold-forming of structural stainless steel sections. In this paper, the level of strength enhancement in a series of cross-section types was established directly by means of tensile material tests on sectioned specimens. These data were supplemented by targeted hardness tests in the regions of high strain gradients (i.e. the corner regions), from which the strength enhancement could be inferred. Following analysis of the experimental results, predictive models were developed such that the strength enhancements could be harnessed in design. These models are included in the UK National Annex [A2] to the stainless steel Eurocode. The research reported in this paper was funded by EPSRC grant GR/S77417/01.

[6] Gardner, L. and Nethercot, D. A. (2004) 'Numerical modeling of stainless steel structural components – A consistent approach'. *Journal of Structural Engineering-ASCE*. **130**(1) pp 1586-1601, doi:10.1061/(ASCE)0733-9445(2004)130:10(1586)
This paper describes, for the first time, a consistent approach to the numerical modelling of stainless steel structures. Models were validated against all available structural stainless steel test results, and numerical prediction of the key performance measures was achieved with a high degree of accuracy. Comparisons with tests and subsequent parametric studies enabled the

development of universal expressions for material stress–strain behaviour, enhanced strength corner properties, initial geometric imperfections (local and global) and residual stresses. The findings have been adopted by other researchers and the work was funded by industry and EPSRC.

4. Details of the impact

Around the world, structures are designed using codes of practice, with the European and North American codes being the most widely adopted. The contents of these codes is typically controlled by a committee of experts and informed by researchers. Members of the Structures Section at Imperial have had long standing involvements in such committees. For example, Professor Nethercot was Chair of the BSI (British Standards Institute) Committee responsible for BS 5950 and the UK input into Eurocode 3, Professor Elghazouli is the UK National Delegate of the International and European Associations of Earthquake Engineering and Professor Gardner is a member of the BSI Committee response for steel structures, the UK National Delegate for the steel and stainless steel Eurocodes, and Chair of the UK Mirror Group for the steel Eurocode. Owing to their widespread use, structural design codes represent the primary means of enabling research to impact on practice. Recent years have seen the introduction or major revision of a number of international stainless steel design standards underpinned by the establishment of a broad experimental database [F], and substantial increases in the use of stainless steel in construction [H,I]. In this case study, it is explained how research conducted at Imperial has made the most substantial contributions [A] to many of the recent developments, particularly in relation to the UK, Europe and North America, though Imperial research has also featured prominently in the development of the upcoming Chinese design standard for stainless steel [A]. The key impacts are summarised below:

UK and European design practice

Based directly on research at Imperial College, a range of improvements have been made to key stainless steel design documents:

- In the UK National Annex [B] to the stainless steel Eurocode, published in 2009, Imperial research has enabled strength enhancements that arise during the manufacture of cold-formed sections to be harnessed and utilised in design, leading to more efficient structural solutions. The method is given in Section NA.3 of the National Annex and is based on research reported in [5]. The method first considers the plastic deformation that is induced during section forming, which relates primarily to the geometry of the formed section, and then the potential for strength enhancement of the material, which relates to the ratio of ultimate to yield strength of the unformed sheet. The outcome from the method is an enhanced yield strength that can be used in subsequent design calculations. The level of enhancement therefore depends upon the properties of the sheet material to be formed and the geometry of the final section, but up to two-fold strength increases can be achieved.
- The continuous strength method [4], described further below, has been published as a UK NCCI [C] in 2013. NCCI refers to ‘Non-Contradictory Complementary Information’ and provides supplementary guidance to the Eurocodes for structural engineers. The CSM is already being used in the construction industry [G,I], with an international stainless steel producer (Ancon Building Products) noting the resulting ‘step-change’ (i.e. substantial increase in design capacities of sections) in their practice [G].
- The first studies [2] to examine the structural performance of lean duplex stainless steel were conducted at Imperial between 2009 and 2012, and based on this work, an amendment to the stainless steel Eurocode to cover this family of grades [D] has now been accepted by the European code committee CEN TC250-SC3. Two other key amendments arising directly from Imperial research, covering cross-section classification and shear buckling, were also accepted in 2012 [A,D].

North American design practice

A new design standard for stainless steel in North America – AISC Design Guide 27 – Structural Stainless Steel [E] was published in 2013, prior to which no guidance for hot-rolled or welded sections was available. The technical basis for this document is linked closely to that of Eurocode 3, but the opportunity to include the findings of recent research has also been taken. Thus, the new code makes very extensive reference to the stainless steel research conducted at Imperial and described in Section 2, with approximately one third of the code references related to research being made to the publications of Professor Gardner [A]. Directly based on this research are the slenderness limits given in Tables 3.1 and 3.2 of the code, the effective area formulae to account for local buckling given in Sections 5.6.1 and 5.6.2, and the design rules specified in Section 9.3 for bolted connections [E]. A major innovation in the code is the inclusion of Annex A – the continuous strength method, which is a new design approach enabling the more efficient design of structural stainless steel elements. The method was developed by Professor Gardner [3,4] and represents a significant departure from existing practice, allowing enhanced member capacities [G] and a more accurate and consistent representation of observed structural behaviour.

Beneficiaries

The durability and favourable mechanical properties of stainless steel make it an ideal material for sustainable construction. With the recent emergence and developments of structural design codes, a growing awareness among structural engineers and architects of its benefits and an increasing availability of structural sections, the use of stainless steel in construction is becoming increasingly widespread [H,I]. Clearly, the research at Imperial [A] enables more efficient structural stainless steel designs, bringing about cost savings [G], more widespread use of the material [A,H,I] and a reduction in the use of resources to the benefit of future generations. The breadth of impact throughout the stainless steel and structural engineering communities, including producers [H], code writers [A] and practitioners [G,I], and global reach of the research, with extensive influence on UK, European, North American and Asian practice [A] have been demonstrated.

5. Sources to corroborate the impact

[A] Letter of corroboration from Associate Director of the Steel Construction Institute, who is Chair of the Stainless Steel Eurocode Evolution Group and author of the AISC Design Guide for Structural Stainless Steel. This letter describes the impact of the Imperial research on International standards and practice.

[B] UK National Annex to Eurocode 3: Design of steel structures – Part 1.4: General rules – Supplementary rules for stainless steel. UK NA to EN 1993-1-4 (2009). http://www.eurocodes.co.uk/PartDetail.aspx?EurocodePartID=19 or on request.

[C] UK NCCI: "The continuous strength method for structural stainless steel design" Available at http://www.steel-ncci.co.uk/Clauses/List-NCCIs or on request

[D] Collection of accepted amendments to the stainless steel Eurocode, all based on Imperial research. Available on request.

[E] AISC Design Guide 27 (2013). Structural Stainless Steel. American Institute of Steel Construction. http://www.aisc.org/store/c-12-design-guides.aspx (product code: AISC 827-13) or on request.

[F] SCI report to Euro Inox: Re-evaluation of EN 1993-1-4 Partial Resistance Factors for Stainless Steel. This report illustrates the magnitude and breadth of the Imperial contribution to the global database of experiments on structural stainless steel. Report available on request

[G] Letter of corroboration from the Product Engineering Manager of Ancon Building Products, explaining the impact of the Imperial research on practice, and the enhanced load-bearing capacities that they have been able to achieve by using our design methods.

[H] Letter of corroboration from the Director of the Outokumpu Research Foundation, Outokumpu being a major global stainless steel producer, emphasising the impact of the Imperial research on producers and fabricators, and the role of Imperial's research in the development of design codes and the expansion of the use of stainless steel in construction.

[I] Letter of corroboration from the Managing Director of Euro Inox, describing the immense impact of the Imperial research on the European stainless steel market.