Cold-Formed Austenitic Stainless Steel Channels with Unfastened Flanges Subject to Web Crippling

Amir M. Yousefi1*, Nariman Saeed1 and Bijan Samali1
1Centre for Infrastructure Engineering, Western Sydney University, NSW, Australia
a.yousefi2@westernsydney.edu.au

ABSTRACT
This research aims to investigate the web crippling strength of cold-formed steel channels fabricated with austenitic stainless steels subject to concentrated transverse forces both experimentally and numerically. The experimental programme is on channel specimens with unfastened flanges and with different web depth to thickness ratios; the tests for channels under both one- and two-flange loading scenarios are covered. For the numerical investigations, detailed nonlinear quasi-static finite element models are used and validated against experimental data. Complementary parametric investigations are then conducted to ascertain the web bearing strengths in terms of various channel sizes, web thicknesses and internal fillet radius. While mechanical properties and material stress-strain shape of different class of stainless steels are different from each other, particularly considering well rounded material behaviour of austenitic steel, no cold-formed stainless steel standard distinguishes between grade of stainless steel, with each standard providing only one equation for different loading scenarios to cover all grades. It is found that the current design equations for stainless steel channels are not reliable to calculate the web bearing strengths of austenitic stainless steel channels and lead to 33% unconservative design. In addition, the web bearing strengths are shown to be higher than those predicted from equations found in the literature for ferritic stainless steel by as much as 34%.

INTRODUCTION
Stainless steels are highly corrosion resistant, durable, ductile and aesthetically appealing materials. They are categorised into five different material grades of austenitic, duplex, ferritic, martensitic as well as precipitation-hardening. Austenitic stainless steel grades possess remarkable formability, ductility, and heat resistance, while they are also non-magnetic. They also typically include 17% to 18% chromium and 8% to 11% nickel, offering excellent resistance against corrosion. Austenitic stainless steels also possess excellent formability, heat resistance and non-magnetic properties. These unique
advantages have led to widespread structural applications of austenitic stainless steel. Due to its fully austenitic structure, the standard chromium-nickel austenitic 304L stainless steel with low-carbon content is one of the most widely used in modern construction, especially for applications with low magnetic permeability requirements (Baddoo (2008); Cashell et al. (2014); Gardner (2019)).

While efforts have been dedicated on determining web crippling strength of cold-formed ferritic stainless steel channels with and without web openings subject to one- and two-flange loading scenarios (e.g. Yousefi et al. (2016;2017a-g;2018a-e;2019a-e)), very limited studies have been carried out on austenitic stainless steel channel sections. In only one previous study, Yousefi et al. (2020) has carried out experimental tests on we crippling of austenitic stainless steel channels. In one of the early studies, Krovink et al. (1994-1995) investigated the web bearing strength of lipped channels under one-flange loading scenarios experimentally. They showed that their experimental results are in general in agreement with the theoretical predictions. However, for the elements with longer bearing lengths, the predicted values seemed to be conservative. In another study, Bock et al. (2013) used analytical simulations to develop a new equation to estimate the web bearing resistance of stainless steel sections. Similarly, Zhou and Young (2006-2007) tested stainless steel tubular sections subject to web bearing failure. However, none of the above studies investigated the performance of unlipped austenitic channels.

Similarly, Li and Young (2017,2019) conducted tests on cold-formed ferritic stainless steel tubular sections under transverse bearing loads. Based on their results, improved design equations were proposed applicable to ferritic stainless steel tubular sections under concentrated bearing loads. In their follow-up studies, Li and Young (2018) also investigated the web bearing strength of high strength tubular sections.

In recent studies by Cai and Young (2019), the web bearing strength of lean duplex stainless steel tubular sections subject to different bearing loads were investigated. However, no cold-formed duplex stainless steel unlipped channels were covered. It should be noted that none of the above studies investigated the behaviour of 304L austenitic stainless steel unlipped channels under web bearing loads.

steel. However, while material response of different families of stainless steels are different from each other, current cold-formed stainless steel standards do not generally classify and distinguish between different groups of stainless steels, with each standard only provides one equation to cover all groups of stainless steel channels for any loading scenario.

The applications of cold-formed austenitic stainless steels in construction industry have been growing rapidly in recent decades. However, due to lack of experimental test data and consequently accurate design equations, the use of austenitic stainless steel channels are mainly limited to structural roofing, particularly where purlins are connected to rafter and roof sections. Such purlin sections are generally under transverse loads, and hence are susceptible to localised web failure. It should be noted that in the current literature, no experimental tests were reported for austenitic 304L stainless steel unlipped channels subject to web crippling. This can be a major obstacle for the wide spread application of these elements. Moreover, current stainless steel design equations for channels subjected to web crippling are mainly based on carbon steel test data with no consideration of different families of stainless steels.

In this paper, the structural performance of cold-formed channels fabricated with austenitic stainless steels subject to concentrated transverse bearing forces is experimentally and analytically investigated. In total, 16 austenitic stainless steel unlipped channels are tested under both one- and two-flange loading scenarios. Subsequently, 88 detailed non-linear finite element (FE) models are developed using quasi-static analysis approach with implicit integration procedure in ABAQUS (2017). The models are then validated against experimental test results. The validated FE models are used to conduct a comprehensive parametric study to (a) investigate the effects of channel size, web thickness and internal fillet radius on the bearing strengths of the austenitic stainless steel channels, and (b) assess the suitability and accuracy of existing design equations in current standards (AS/NZS 4673 (2001), SEI/ASCE-8 (2002), EN 1993-1-4 (2006), and EN 1993-1-3 (2006)) as well as those recently suggested by Yousefi et al. (2018a). Finally, using both experimental and analytical results, new web bearing strength design equations are proposed for cold-formed austenitic stainless steel channels and their reliability is investigated under both one- and two-flange loading scenarios.

EXPERIMENTAL INVESTIGATION
Test Specimens
In total, 16 unlipped channels were considered in the laboratory investigation. The channel specimens were press-baked from austenitic stainless steel grade G304L sheets with web height to thickness ratio (h/t) ranging from 114.3 to 172.5 and web depths of 175 to 200 mm. The length (L) of each channel was selected based on the threefold of its height (as recommended by AISI S100 (2016)) with the addition of the length of bearing plates and load support blocks. The lab measured cross-section details for all the tested specimens are presented in Table 1. The specimens were loaded through the flanges for interior-one-flange (IOF), interior-two-flange (ITF) and end-two-flange (ETF) loading and through the load transverse block for end-one-flange (EOF) loading. The loads were applied at the middle of the specimens for IOF and EOF loadings, and applied at the end of the specimens for EOF and ETF loadings.

Specimens Labelling
The specimens were labelled in order to identify the nominal specimen dimensions, thickness and the bearing plates’ length. For instance, the label "200×75-t2.0-P100-r5.5" is exemplified as following. The annotations "200" and "75" refer to the nominal specimen’s depth and width for unit of millimetres, respectively. The annotation "P100" indicates the length of bearing plates for unit of millimetres (P=100 mm), and "r5.5" denotes the internal bend radius (r=5.5 mm). The annotation "A0" indicates channel section without web openings. For the numerical investigations, the same denotations were applied for model labelling.

Material Testing
In total, 6 tensile coupon specimens were tested to obtain the material behaviour of the tested specimens. Three tensile coupons have been cut from the 4 mm steel thick and three tensile coupons from the 6 mm steel thick of the austenitic sheets, from which the test specimens were manufactured. The coupons were provided as per both ISO 6892-1 (2009) and AISI S909 (2013), and loaded under a 100 kN capacity Instron tensile testing machine. As per AISI S909 (2013), coupons have been taken from areas where cold-working stresses will not affect the results. Corresponding hot-rolled steel materials can be found in Rezvani et al. (2015).

Laboratory Test Rig and Procedure
As shown in Figs. 1 to 4, the test specimens were loaded under one- and two-flange loading scenarios according to AISI S100 (2016). In terms of setting up for IOF loading scenario, a pair channel was used to provide symmetrical loading arrangement through bolting their webs to support blocks at the two ends of the channels. High strength steel material was used for the bearing plate located at the middle of the channel specimens to transfer the vertical loads via the channel flanges. At each end of the channels, half rounds were considered in the vertical line of vertical action of the load. In terms of the testing setup for EOF loading scenario, a pair channel was used to provide symmetrical loading arrangement achieved by bolting their webs to the load transfer block at the middle of the channels, where the transverse load was applied to the channels. At each end of the channels, the same bearing plates and half rounds were used in the vertical line of the vertical load action. The Instron Machine enforced a displacement-controlled load on the channels driving the actuator at a regular constant loading speed of about 0.05 (mm/min). Figs. 1 to 4 show the illustrative front and end view of the testing arrangements. Fig. 1, Fig. 2, Fig. 3, and Fig. 4 present the testing set-up for tested channels subject to one- and two-flange loading scenarios.

![Image of experimental setup](image.jpg)

**Figure 1. Experimental set-up for channels under Interior-Two-Flange (ITF) loading.**
Testing Results
As mentioned before, in total 16 channel specimens with various thicknesses and internal fillet radius have been tested under both one- and two-flange loading scenarios. The experimental ultimate web bearing load values for single web, specified as FLAB, are presented in Table 1. The failure occurred at mid-length of the channels for the IOF and ITF load scenarios, while the failure occurred at two ends and one end of the channel flanges for the EOF and ETF load scenarios, respectively. This is due to the fact that load was applied and transferred through load baring plate to the channel flanges at mid-length in IOF and ITF loadings, while load was applied and transferred through load transfer block to channel webs at mid-length in EOF loading and on top of bearing plate at one end on ETF loading.

Figure 2. Experimental set-up for channels under Interior-One-Flange (IOF) loading.

Figure 3. Experimental set-up for channels under End-Two-Flange (ETF) loading.
Figure 4. Experimental set-up for channels under End-One-Flange (EOF) loading.

Table 1 Experimental and finite element ultimate web bearing strengths

<table>
<thead>
<tr>
<th>Channel</th>
<th>Web depth (mm)</th>
<th>Web thickness (mm)</th>
<th>Channel length (mm)</th>
<th>Single web experimental ultimate load (kN)</th>
<th>Single web finite element load (kN)</th>
<th>Comparison</th>
<th>F_{LAB}/F_{FEA}</th>
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</thead>
<tbody>
<tr>
<td><strong>ITF loading scenario</strong></td>
<td></td>
<td></td>
<td></td>
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<td></td>
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<tr>
<td>175x60-t6.0-P50-r5.5</td>
<td>177.67</td>
<td>5.89</td>
<td>574.50</td>
<td>104.28</td>
<td>105.27</td>
<td>0.99</td>
<td></td>
</tr>
<tr>
<td>175x60-t6.0-P50-r7.8</td>
<td>178.40</td>
<td>5.79</td>
<td>575.00</td>
<td>102.54</td>
<td>103.12</td>
<td>0.99</td>
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</tr>
<tr>
<td>200x75-t4.0-P100-r3.5</td>
<td>201.24</td>
<td>3.94</td>
<td>700.00</td>
<td>53.15</td>
<td>54.24</td>
<td>0.98</td>
<td></td>
</tr>
<tr>
<td>200x75-t4.0-P100-r7.8</td>
<td>202.49</td>
<td>3.89</td>
<td>700.00</td>
<td>45.35</td>
<td>46.12</td>
<td>0.98</td>
<td></td>
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<tr>
<td><strong>ETF loading scenario</strong></td>
<td></td>
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</tr>
<tr>
<td>175x60-t6.0-P50-r5.5</td>
<td>177.25</td>
<td>5.86</td>
<td>315.00</td>
<td>35.67</td>
<td>34.95</td>
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<tr>
<td>175x60-t6.0-P50-r7.8</td>
<td>178.46</td>
<td>5.92</td>
<td>315.00</td>
<td>31.76</td>
<td>31.26</td>
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<tr>
<td>200x75-t4.0-P100-r3.5</td>
<td>201.99</td>
<td>3.90</td>
<td>400.00</td>
<td>21.08</td>
<td>21.55</td>
<td>0.98</td>
<td></td>
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<tr>
<td>200x75-t4.0-P100-r7.8</td>
<td>202.75</td>
<td>3.91</td>
<td>400.33</td>
<td>17.54</td>
<td>18.03</td>
<td>0.97</td>
<td></td>
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<tr>
<td><strong>Mean</strong></td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td>1.00</td>
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<tr>
<td><strong>CoV</strong></td>
<td></td>
<td></td>
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<td></td>
<td></td>
<td></td>
<td>0.02</td>
</tr>
</tbody>
</table>
NUMERICAL INVESTIGATION

The general-application FE program ABAQUS (2017) was used in order to simulate the non-linear behaviour of the tested specimens by modelling the channels, bearing plates, as well as the applied loading condition including the bearing plates and support blocks. The material properties and cross section dimensions were based on the values measured in the lab. To analyse the FE models, quasi-static analysis approach with an implicit integration procedure was utilized, which is consistent with the Natário (2014) and Mohammadjani et al., (2017) approach using explicit integration procedure. The advantages of such analysis method is to include the complex material nonlinearity and contact behaviour as described in the previous works by Yousefi et al. (2018a). Specific detailed modelling techniques are summarised in the following subsection.

Element Type and Material Properties
The S4R thin shell element was used to model the channel sections. This element, which is a four-node double curved thin or thick element having reduced integration, is appropriate for complicated buckling analysis behaviour (Yousefi et al. (2018a)). The load blocks and bearing plates were also modelled using general purpose C3D8R element. This element is generally defined by eight nodes with three degrees of freedom in translation, and is most suitable for modelling structures with large deflections, plasticity and high strain capabilities. The bearing plates were fabricated using high strength steel with a nominal yield strength of 560 MPa and a thickness of 25 mm. Such properties were considered for the finite element modelling of the bearing plates. The centreline dimension lines of the channel sections were modelled in the numerical modelling. The mean engineering material curve determined from the material testing was converted into true material curve for modelling, as per ABAQUS manual (2017).

Geometry and Mesh
Fig. 7 and Fig. 8 show the finite element model for the channels under IOF and EOF loading scenarios, respectively. Due to the symmetry of the test specimens about principal axes and to reduce the computational time, only half of the testing arrangements were modelled. The bearing plates, the load transfer block, the channel sections and the contact between the bearing plates and the channel section and load transfer block were modelled. Contact surfaces are defined between the bearing plate and the cold-formed steel section, and between the load transfer block and cold-formed steel section. "Surface to surface” contact was used for contact modelling between surfaces. The two contact surfaces were
not allowed to penetrate each other. The dimensions of the modelled channels are given in Table 1, while the typical FE meshes for the load blocks, bearing plates, and channel sections are illustrated in Figs. 5 to 8. The FE mesh sizes of 5×5 and 8×8 mm were respectively used for the channel sections, and the support blocks and bearing plates to provide a balance between accuracy and computational time efficiency. It should be mentioned that, to uniform transferring of loads from flanges to web in IOF, ITF and ETF loading scenarios and from web to flanges in EOF loading scenario, a finer mesh size of at least fifteen elements have been used for the flanges conjunction and web.

**Loading and Boundary Conditions**

The channels were loaded through the flanges for IOF, ITF, and ETF loadings and through the load transverse block for EOF loading by using displacement control analyses. Hinge supports were simulated by two half rounds in the line of action of the force. A reference point was defined on top of the bearing plates for IOF, ITF, and ETF loadings (or the support block for EOF) in order to apply the vertical displacement. The plates and block were modelled using analytical solid plates with a reference point to constrain the top surfaces. Symmetry surface nodes were restraint against x direction translation as well as rotation about y and z axes. For IOF loading scenario a pair channel was bolted through their webs to support blocks at the two ends, however, for EOF loading scenario a pair channel was bolted through their webs at the middle of the channels where transverse load is applied to the channels. Cartesian connector, “CONN3D2”, was used in order to model the bolts used to connect the pair channel to the support blocks in IOF and EOF loading scenarios (see Figs 7 and 8). The interface contacts between the channels, bearing plates and blocks were modelled using "surface to surface" contact option in ABAQUS (20170, while the channel flanges were considered as slave surface and bearing plates as master surface. No penetration was allowed in the contact surfaces.

![Figure 5. Finite Element (FE) modeling of channels under Interior-Two-Flange (ITF) loading.](image)
Figure 6. Finite Element (FE) modeling of channels under End-Two-Flange (ETF) loading.

Figure 7. Finite Element (FE) modeling of channels under Interior-One-Flange (IOF) loading.

Figure 8. Finite Element (FE) modeling of channels under End-One-Flange (EOF) loading.

Finite Element (FE) Validation
The FEA and experimental results were compared in order to check and verify the accuracy of the developed FE models. Table 1 presents the experimental and numerical comparison in regard to ultimate web bearing loads for single web ($F_{LAB}$ and $F_{FEA}$). The results show a very good agreement between the experimental measurements and the analytical predictions for all the models. The average ratio of the $F_{LAB}/F_{FEA}$ is 1.00, with the variation coefficient of 0.02. The maximum differences between experimental and FEA results were observed for 200×75-t4.0-P100-r3.5 and 200×75-t4.0-P100-r7.8; however, in both cases the error was less than 3% under EOF and ETF loading scenarios. It is also shown in Figs. 5 to 8 that the developed FE models could accurately predict the web bearing mode of
failure for the tested channels under both loading scenarios. It is clear that a good match was achieved for both cases.

WEB CRIPPLING STRENGTH COMPARISON WITH PREVIOUS STUDY

In this section, the accuracy of web bearing strength design equations recently proposed by Yousefi et al. (2018a) for ferritic stainless steel channels is investigated against the laboratory and numerical results of this study on austenitic stainless steel members. These design equations were endorsed for cold-formed stainless channels under one-flange loading scenarios as follows:

IOF loading scenario:

\[ P_p = 10.5t^2f_y \sin \theta \left[ 1 - 0.28 \sqrt{\frac{R}{t}} \right] \left[ 1 + 0.23 \sqrt{\frac{P}{t}} \right] \left[ 1 - 0.01 \sqrt{\frac{h}{t}} \right] \] (1)

EOF loading scenario:

\[ P_p = 7t^2f_y \sin \theta \left[ 1 - 0.10 \sqrt{\frac{R}{t}} \right] \left[ 1 + 0.23 \sqrt{\frac{P}{t}} \right] \left[ 1 - 0.04 \sqrt{\frac{h}{t}} \right] \] (2)

The above equations are with the limitation of \( P/h \leq 0.61 \), \( P/t \leq 70.92 \), \( a/h \leq 0.8 \), \( \theta = 90^\circ \) and \( h/t \leq 175 \).

The results in general indicate that these design equations are unreliable and un-conservative for applying to the austenitic stainless steel channels under both loading scenarios. The mean value of the calculated web bearing strengths for channels under IOF and EOF loading scenarios were 0.88 and 0.66 with the coefficient of variations of 0.11 and 0.10, respectively. This suggests that the design equations developed based on ferritic steel channels lead to considerably un-conservative results (up to 34%) for cold-formed unlipped stainless steel austenitic channels. This conclusion is in agreement with the results of the code proposed equations as discussed in the previous section.
DESIGN COMPARISONS FOR COLD-FORMED AUSTENITIC STAINLESS STEEL CHANNELS

To assess the suitability and accuracy of existing stainless steel design equations to be used for austenitic stainless steel channels, the web bearing strengths predicted from the current standards are compared against the values obtained from the experimental tests as well as the validated detailed FE models from parametric investigation. The standards covered in the design comparisons are AS/NZS 4673 (2001), SEI/ASCE-8 (2002), and EN 1993-1-4 (2006) which are provide guidelines for the design of stainless steel structural members.

The accuracy of EN 1993-1-4 (2006) design equation was slightly better, and the average of the experimental to predicted strength ratios increased to 0.76 (coefficient of variation of 0.12). This implies that the design standards generally overestimate (up to 33%) the web bearing strength of stainless steel elements under IOF load scenario.

The ratios of the experimental to the predicted strength values obtained based on AS/NZS 4673 (2001) and SEI/ASCE-8 (2002) were on average 0.95 and 0.86 with the coefficient of variations of 0.09 and 0.11, respectively. In this case, EN 1993-1-4 (2006) led to more accurate results with the mean experimental to the predicted strength ratios of 1.08 and coefficient of variations of 0.10. It can be concluded that while EN 1993-1-4 (2006) provides conservative (up to 8%) predictions, AS/NZS 4673 (2001) and SEI/ASCE-8 (2002) generally overestimate (up to 14%) the web bearing strength of stainless steel elements under EOF load condition.

AS/NZS 4673 (2001), SEI/ASCE-8 (2002), and EN 1993-1-4 (2006) proposed equations lead to the experimental to the predicted strength ratios of on average 0.57, 0.60 and 0.67 with the coefficient of variations of 0.21, 0.19 and 0.19, respectively. This implies that, in general, all these design codes significantly overestimate (up to 43%) the web bearing strength of stainless steel elements under ITF load condition.

It can be seen that under ETF loading scenario, both AS/NZS 4673 (2001) and SEI/ASCE-8 (2002) resulted in the mean experimental to the predicted strength ratio of 0.74 with the coefficient of variations of 0.18, while EN 1993-1-4 (2006) led to the experimental to the predicted values of on average 0.82
with the coefficient of variations of 0.18. This means that all these design standards overestimate (up to 26%) the web baring strength of stainless steel elements under ITF load condition.

The results confirm that current design standards generally overestimate the web baring strength of austenitic stainless steel channels under all different loading scenarios, and therefore, can lead to considerably unsafe design solutions. This highlights the need to develop more efficient design equations to predict the web bearing strength of austenitic stainless steel channels.

**CONCLUSION**

This research investigated the web crippling strength of cold-formed steel channels fabricated with austenitic stainless steels subject to web crippling both experimentally and numerically. The experimental programme was on channel specimens with unfastened flanges and with different web depth to thickness ratios; the tests for channels under both one- and two-flange loading scenarios were covered. For the numerical investigations, detailed nonlinear quasi-static finite element models were used and validated against experimental data. Complementary parametric investigations were then conducted to ascertain the web bearing strengths in terms of various channel sizes, web thicknesses and internal fillet radius. While mechanical properties and material stress-strain shape of different class of stainless steels are different from each other, particularly considering well rounded material behaviour of austenitic steel, no cold-formed stainless steel standard distinguished between grade of stainless steel, with each standard providing only one equation for different loading scenarios to cover all grades. It is found that the current design equations for stainless steel channels are not reliable to calculate the web bearing strengths of austenitic stainless steel channels and lead to 33% unconservative design. In addition, the web bearing strengths are shown to be higher than those predicted from equations found in the literature for ferritic stainless steel by as much as 34%.

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BIOGRAPHY

Dr Amir M. Yousefi: Dr Yousefi is a Postdoctoral Research Fellow at Western Sydney University conducting research and developments on steel structures particularly cold-formed stainless steel structural components. Prior to that, Amir was granted University of Auckland Doctoral Scholarship and graduated with PhD in Civil/Structural Engineering. Amir is Professional Member of Engineers Australia and his research interests including: cold-formed steel, web crippling, bolted connections, and progressive collapse.

Dr Nariman Saeed: Dr. Saeed is a lecturer at the Centre for Infrastructure Engineering at Western Sydney university. Dr Saeed is a Fellow member of Engineers Australia and has become Chartered as a Professional structural Engineer. He obtained his PhD from the University of Queensland at 2015. Dr Saeed has been CI for several research-based consultancy projects with the revenue of greater than $1milion.

Prof Bijan Samali: Professor Samali is the director of Centre for Infrastructure Engineering at Western Sydney University. Prior to joining Western Sydney University, Professor Samali held a Personal Chair in Structural Engineering at UTS. He is the author or co-author of over 500 scholarly publications (including over 150 journal publications), on a wide range of topics in civil and structural engineering. He has also been involved with several major projects as a specialist consultant over the years.