A. Project Information

Project: Cross-section Stability of Structural Steel
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Abstract

Local buckling, is an issue that hot-rolled steel design and construction generally tries to avoid through judicious selection of locally stable cross-sections. While slender cross-sections due see use in certain specific applications, in general, the additional complications in the design Specification procedures, limitations in analysis software (which cannot easily include locally unstable sections), and over-riding concerns about serviceability over strength have discouraged the use of slender sections for many years. Over this time, while our basic philosophies with respect to cross-section stability have stayed the same, steel has not stagnated. In particular, changes in the yield stress of steel including the prevalence of high strength steel (50 and 65 ksi) and the future emergence of high performance (70 and 100 ksi) and ultra high strength steel (>100 ksi) in buildings make cross-section stability an increasingly important issue, and one that deserves re-thinking so that future opportunities are not missed.

Proposed herein is a research plan to leverage and expand recent findings in cold-formed steel research that point to new and efficient ways to handle cross-section stability in design. Cross-section stability is of increasing importance as yield stress is increased. The research will require a significant computational and analytical effort. Funds for experimental validation will be sought from other agencies by using the money provided in this grant as a demonstration of the industry's interest in the work. The research will provide partial support and educational opportunities in structural steel for a Ph.D. student and two M.S. students.

Research objectives for the proposed effort in cross-section stability in hot-rolled steel include:

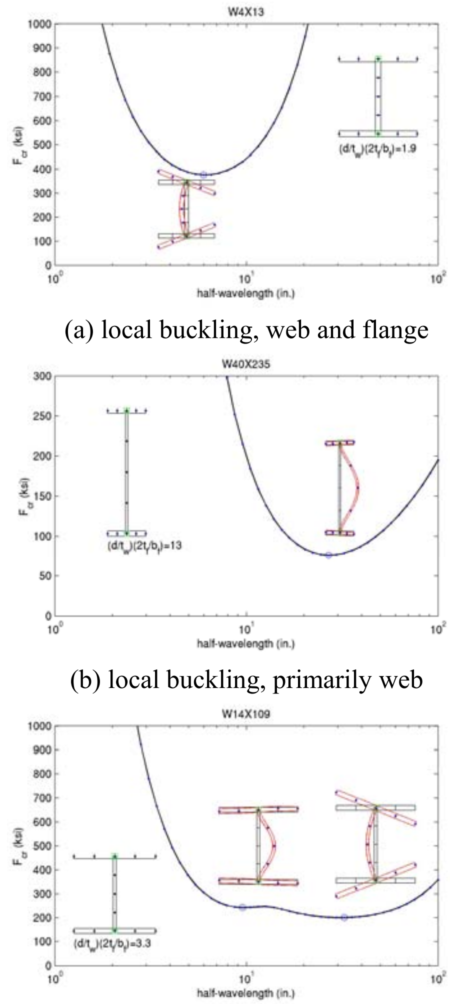
- take better advantage of the opportunities afforded by everyday use of high strength steel, and lay the ground work for leveraging future opportunities in ultra high strength steels,
- open opportunities to change the current balance between serviceability and strength by providing new methods for evaluating cross-section shape optimization,
- enable advanced analysis methods for frame stability to handle noncompact and slender cross-sections in a rational way,
- address technical issues related to cross-section stability that exist in the Specification today (consistent treatment of web/flange interaction, Q-factor approach, etc.), and
- leverage recent progress in cold-formed steel for use in hot-rolled steel construction.

Taken together, these research goals aim to provide a simple, robust, design method for structural steel that treats cross-section stability with ease, and readily embraces the numerous noncompact and slender sections that will result with ultra high strength steels, while at the same time provides obvious means for shape optimization of structural steel shapes.

B. Project Description

B1 Analysis of cross-section stability

Central to the ideas of this proposal is the ease with which we can today perform an analysis of cross-section stability. For example, the analyses of Figure 1 were performed in the PI's own open source finite strip analysis program, and provide the local buckling modes of common AISC W-shapes in axial compression. Analyses such as these can readily replace the tabled plate buckling solutions for stiffened elements, unstiffened elements, and the like that we had to rely on in the past. A proper cross-section stability analysis can provide a more accurate prediction of elastic and inelastic cross-section stability and provides a more direct way to understand the behavior of the cross-section as a whole instead of attempting to make idealizations about the flange or web behavior in isolation.



(a) local buckling, web and flange

(b) local buckling, primarily web

(c) multiple local buckling modes

Figure 1 Finite strip analysis of local buckling of common W-shapes in compression
(using the PI's open source program CUFSM)

Finite strip analysis (Cheung and Tham 1998) provides an alternative to conventional finite element analysis that is nicely suited for exploration of cross-section stability. The applicability of the finite strip method to structural steel shapes has long been known, and a good example of the early work in cross-section stability of W-shapes is provided by Hancock (1978). The work of Dawe and Kulak (1984a,b 1986) demonstrated through comparison with relatively extensive experimental data that finite strip methods[1] could predict local buckling accurately. Bradford and his colleagues have also provided significant insight using this method, including examination of cross-section slenderness limits in beams-columns (Bradford 1991), stability analysis into the inelastic regime (Azhari and Bradford 1992), and shear buckling (Bradford 1996). Finite strip analysis, which was once only a tool for researchers to use on workstation class machines can now be completed in a matter of seconds on a garden variety PC. Where once simplifications and design charts were the goal, now an engineer can perform finite strip analysis of any cross-section with ease.

With current desktop computing power, availability of open source code (Schafer 2004), new analysis methods that allow the user to isolate individual cross-section buckling modes (Adany and Schafer 2004), and recent progress in design methods for locally unstable sections, it seems that now is a good time to take a fresh look at cross-section stability of structural steel shapes.

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[1] Dawe and Kulak did not use the word "finite strip" to describe their computational model, but the selected shape functions and analysis procedure are readily recognized today as finite strip, rather than finite element analysis.

B2 New ideas in cross-section stability design: an introduction to the Direct Strength Method

Over the last 10 years a new method for cross-section stability design: the Direct Strength Method, has been developed for use in cold-formed steel. The method uses a computational stability analysis of the cross-section, typically a finite strip analysis, as the key step in determining the strength of open cross-sections subject to a variety of different potential instabilities. A proper cross-section stability analysis is able to account for the interaction of the elements of the cross-section in an efficient manner, and thus provide a more reliable indicator of true behavior. A goal of the research proposed here is to investigate the application of the Direct Strength Method (DSM) to structural steel shapes, and to provide the necessary research advances to make this a viable option for the design of noncompact and slender structural steel shapes.

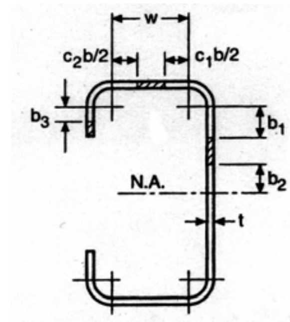

Figure 2 Effective Width

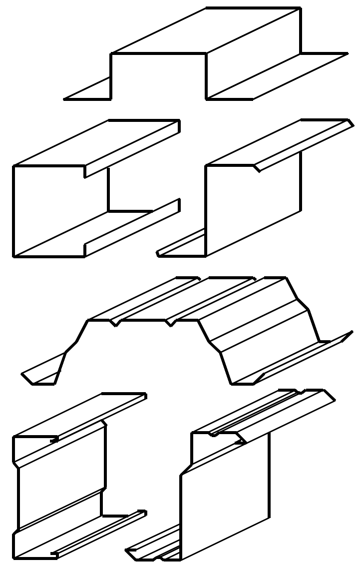
Figure 3 (above) Typical cold-formed steel shapes created in the U.S. in the 1940's and still used today (below) more optimized shapes

DSM aims to solve one of the most significant problems with designing thin-walled sections: locally unstable sections are too much of a mess for the design engineer to bother with: "Anyone who has ever attempted to design a light-gage member following the Specification provisions probably realized how tedious and complex the process was." Newman (1997). No wonder, the rules for the effective width determination of a lipped channel (Figure 2) require pages of calculation and iteration. Does this complication have an impact? It seems to, while the adoption of design specifications for cold-formed steel in the 1940's spurred on a new industry, these same codes now appear to hinder innovation (Figure 3). DSM can provide the solution with one cross-section analysis, one equation, and no iteration. The goal of DSM is to provide a design method which is robust enough to allow engineers to realistically explore novel cross-sections, yet make this exploration simple. What would happen if such a tool was used to take a fresh look at hot-rolled steel structural shapes?

DSM was first formalized for cold-formed steel beams undergoing local or distortional buckling (Figure 4, Schafer and Peköz 1998, 1999) and then for pin-ended columns in local, distortional or flexural-torsional buckling (Schafer 2002). DSM's reliability, based on 267 column tests and 569 beam tests, equals existing design methods. Comparisons with existing design methods by others have been favorable (Quispe and Hancock 2002, Yan and Young 2003, Yang and Hancock 2003). DSM has been noted as a potential method for future design in recent textbooks (Yu 2000, Hancock et al. 2001, Ghersi et al. 2002) and review papers (Davies 2000 and Hancock 2003). DSM has recently passed an important watermark, by being formally adopted for cold-formed steel beams and columns as a new alternative method in the 2004 supplement to the AISI North American Specification (NAS 2004).

DSM's member capacity prediction, considering cross-section instability, is straightforward. For example, for local buckling with the potential to interact with lateral-torsional buckling, DSM's prediction of the strength ($M_{n\ell}$), as approved for use in cold-formed steel design is:

$$\text{for } \lambda_\ell \le 0.776 \qquad M_{n\ell} = M_{ne} \tag{1}$$

$$\text{for } \lambda_\ell > 0.776 \qquad M_{n\ell} = \left(1 - 0.15\left(\frac{M_{cr\ell}}{M_{ne}}\right)^{0.4}\right)\left(\frac{M_{cr\ell}}{M_{ne}}\right)^{0.4} M_{ne} \tag{2}$$

$$\text{where } \lambda_\ell = \sqrt{M_{ne}/M_{cr\ell}} \tag{3}$$

The local slenderness is λ_ℓ, $M_{cr\ell}$ is the critical elastic local buckling moment, and M_{ne} is the lateral-torsional buckling strength, if the section is laterally braced M_{ne} = yield moment, M_y. The curve generated by Eq.'s 1 and 2 is given in Figure 4 and may be compared against the "x's" in the figure which are the available experimental data. The primary effort in DSM is performing the cross-section stability analysis, the reward is that once this analysis is performed simple expressions (e.g., Eq. 2) can predict complex phenomena. DSM provides a particularly efficient solution for the complicated case of distortional buckling, a limit state prevalent in sections with flanges stiffened by lips, and one that becomes more prevalent for higher strength steels.

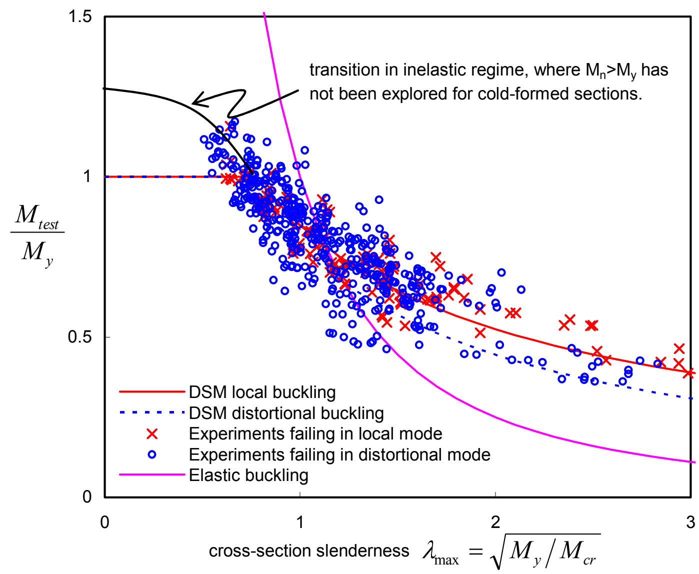

Figure 4 DSM predictions compared with experimental data from 569 cold-formed steel laterally braced beams, note the elastic buckling curve shows regimes where elastic post-buckling is assumed in the prediction equations, also extension to structural steel will require closer examination of inelastic regime $M_n \rightarrow M_p$

One concern with integrating numerical methods into design is creating a "black box". Open source software helps avoid this problem by being more like the handbooks engineers have always relied on: easy to use solutions that are openly documented and demonstrate the application of basic mechanics. In the future we may rely on programs such as CUFSM[2] where engineers can solve classic plate buckling, or member buckling problems, and always be able to explore the actual code.

Significant research remains to extend DSM to structural steel. Thickness variations common in hot-rolled steel do not exist in cold-formed steel and create unique cross-section stability modes. For example, the multiple local buckling modes as illustrated in Figure 1c must be examined further. Inelastic buckling is far more important in structural steel than in cold-formed steel – thus the influence of residual stresses and strain hardening must be explicitly considered (as was detailed in early research on Gr. 50 steel Adams 1966, Lay 1965, Yura and Driscoll 1965). Existing test data on structural steel shapes must be gathered and an initial study performed to consider the adequacy of existing DSM equations for local buckling and the calibration of new expressions. The progress made on DSM for cold-formed steel provides a solid foundation for extension to noncompact and slender structural steel shapes, but much work remains.

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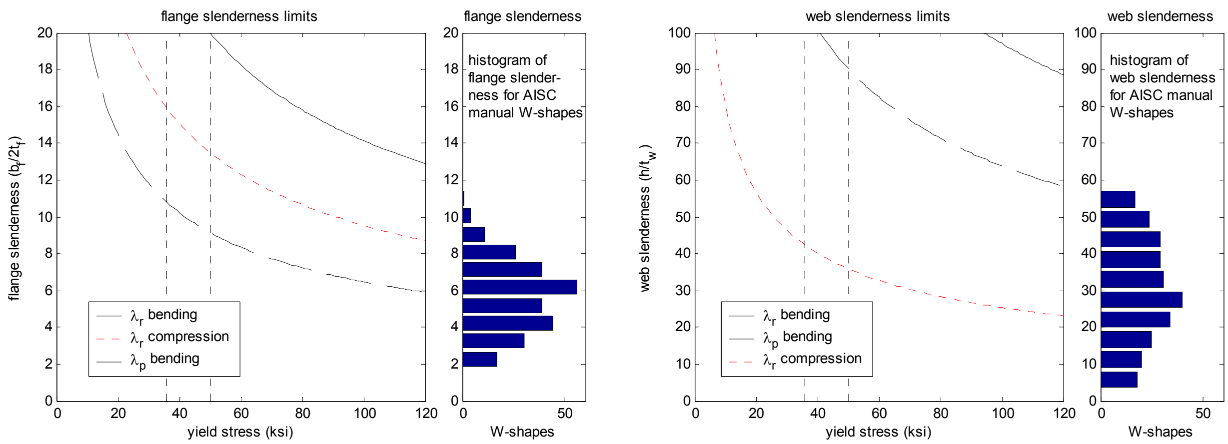
[2] CUFSM (Schafer 2004) was written by the PI, has been distributed and maintained as open source code since 1997, and currently users exist in at least 21 different countries.

B3 High and ultra high strength steel and the role of cross-section stability on current structural steel shapes

As we increase the yield stress of structural steel we increase the potential for cross-section stability to control the strength. Metallurgists have not been able to appreciably change the modulus of steel, but the yield stress has certainly seen significant changes from mild steel, 36 ksi, to high-strength steel 50, 65 and sometimes even 70 ksi (e.g, A913) to high performance steel 70 and 100 ksi, and today the slow but steady emergence of ultra high-strength steel > 100 ksi. If we want to take full advantage of these changes we need to embrace new methods for predicting cross-section stability, and then employ these methods to (1) improve and create new structural steel shapes, and (2) increase the power of our analytical tools. This stands to open up new markets for steel products and to help the construction industry capitalize on the significant changes that have occurred in our abilities to efficiently create ever higher yield stress steels.



(a) flange slenderness (b) web slenderness

Figure 5 Impact of yield stress on slenderness limits compared with current slenderness of W-shapes

An illustration of the impact of higher yield stress steels on cross-section stability is provided in Figure 5. Consider the flange slenderness limits of the AISC Specification as shown in Figure 5a, as the yield stress increases these limits decrease – the histogram on the right of Figure 5a provides the flange slenderness of all W-shapes currently listed in the AISC Manual. The strictest limit is the flange slenderness limit for fully compact beams (λ_p bending). How many W-shapes become noncompact as the yield stress increases? At 36 ksi, only 1 of the 267 standard W-shapes is noncompact, at 50 ksi 11 W-shapes, at 65 ksi 27 W-shapes, at 70 ksi 39, at 100 ksi 94, at 120 ksi 119 W-shapes. As we reach towards ultra high strength steels nearly ½ of our standard W-shapes become noncompact. Web slenderness is portrayed in Figure 5b, as the figure illustrates, for columns the number of W-shapes that have slender webs increases dramatically. While not all W-Shapes would be used as columns, many of the W12 and W14's which are compact at 36 and 50 ksi reach the slender regime as yield stresses push up to 100 ksi.

Full cross-section stability analysis would provide a somewhat more nuanced picture than Figure 5. Ignoring web/flange interaction in the development of the λ limits employed in Figure 5 may be misleading. Consider, for web slenderness (Figure 5b) for 36 ksi and even 50 ksi steel the flange was generally compact and stable, thus it is possible to approximately consider the web in isolation of the flange. However, for higher strength steels web/flange interaction from the noncompact flanges would become a greater issue. Further, issues which are readily apparent in the cross-section analysis such as multiple local buckling modes (Figure 1c) are not reflected in current approaches. Researchers examining high performance steel (70 ksi yield) have shown that existing compactness requirement (in this case from AASHTO, not AISC) may be adequate from a strength standpoint but misleading from a ductility standpoint (Yakel et al. 2002).

Employing high strength and eventually ultra high strength steels brings an enormous number of questions to our design specification. What will happen when we move so radically away from our testing and experience base? How can these steels be made weldable and avoid fatigue and fracture problems? What is the impact of lost ductility and strain hardening on our design assumptions? Of course, there are many additional issues as well, but these issues represent opportunities as well as challenges for modern structural steel. While this proposal cannot begin to address all the issues related with embracing higher strength steels, DSM's ability to simplify design of sections with slender and noncompact cross-sections represents an area of significant opportunity, and of growing importance for higher strength steels.

B4 Shape optimization and research to re-balance the serviceability vs. strength equation

To embrace the potential of high strength steel and ultra high strength steels it is proposed to re-examine our current structural steel sections with an eye towards creating new sections that (1) take advantage of the improved strength, and (2) improve the stiffness so that serviceability does not control the majority of applications.

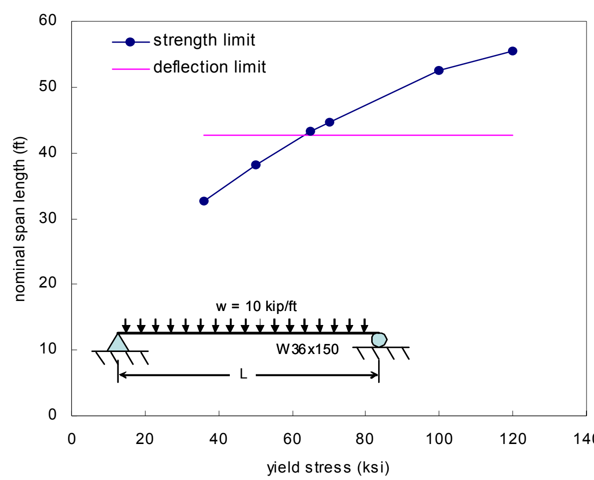


Figure 6 Simplified example of the limits of increasing yield strength on conventional sections, span length as a function of yield stress for a fully laterally braced W36x150 under 10 kip/ft uniform load (nominal calculation: no safety or resistance factors)

Conventional wisdom from structural steel designers suggests that in modern steel design, with high strength steel W-shapes and up-to-date specifications, serviceability controls member design as much as, or more often than, strength considerations. As a result, in many (some say most) design situations the advantage of a high strength steel A992 W-shape is not its elevated yield stress, but simply its reduced cost from its older A36 cousin. An example bears this conventional wisdom out. The maximum nominal span length for a simply supported, fully laterally braced W36x150 with a 10 kip/ft uniform load is shown in Figure 6. Considering a deflection limit of L/180 serviceability controls for yield stresses higher than ~50 ksi.

The example of Figure 6 is not without flaws, but it illustrates the point, if we do nothing to our structural shapes serviceability will control and the advantage of higher strength steels will be lost. Currently, for A36 beams strength typically controls, for Gr. 50 and higher, serviceability often controls, and the situation is only further exacerbated for higher yield steels. We need to re-balance this serviceability vs. strength equation.

Investigations of structural shape optimization invariably involve numerous conditions outside of simple strength and stability concerns. Clearly manufacturing cost is the over-riding issue, and drive any final optimization. However, sometimes the mechanics can suggest where better optimal designs might be found. The work proposed here would focus on this aspect of structural shape optimization and to be successful would have to be followed by a hard look at manufacturing processes. Consider two levels of optimization:

optimization level 1: primarily move material around in existing sections,

optimization level 2: explore entirely new shapes.

An example of optimization level 1 is illustrated in Figure 7. Here the W36x150 of Figure 6 has been modified: the web thickness was reduced by 40% and the additional material was added to the flanges. The resulting section is 34% stiffer, and has the same depth and weight, but it is also noncompact even for A36 steel. This cross-section ultimately gives up some strength to gain stiffness and re-balances the serviceability vs. strength line, such that yield stresses as high as ~80 ksi are effectively employed. The strength prediction for this example used a variation of DSM similar to Eq.'s 1-3. Formal optimization with agreed upon objectives are needed to provide detailed and useful shape optimization, but the example illustrates the large potential benefits of such work.

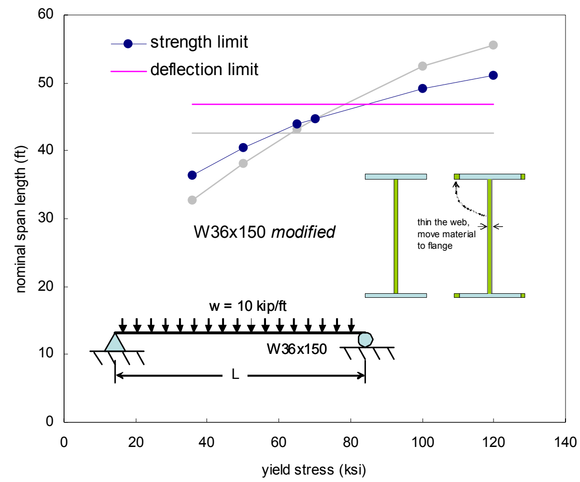


Figure 7 Example of benefits of shape optimization for a conventional W-shape when using high strength steel, modified section has the same weight/foot and depth as original W36x150, material from the web is moved to the flange, but the section is noncompact essentially over all yield stress (a variation of DSM is used to approximate the strength shown.)

Level 2 optimization, where entirely new shapes are explored is a much longer term endeavor and one that must be more closely tied to the realistic possibilities of modern manufacturing technology. The applicability of DSM's methods to more complicated cross-sections has been excellent in cold-formed steel; such as in the optimized sections of Figure 3, and promising work has been completed on complicated extrusions common in Aluminum, as shown in Figure 8. Thus, it would seem that manufacturing, not imagination, would be the limiting constraint on level 2 optimization. Potential modifications that could be explored for structural steel beams include: longitudinal web stiffeners, corrugated webs, flange edge stiffeners, and others. For columns, intermediate and edge stiffeners, or other modifications, may have benefits. More complicated cross-sections will result in more interesting results from the cross-section stability analysis (i.e., Figure 1). In particular, the addition of stiffeners will require the examination of at least 1 additional stability mode, typically termed distortional buckling in cold-formed steel literature. However, this new mode does not make the DSM strength prediction more complicated, as a set of expressions similar to Eq.'s 1 – 3 can account for these new modes (see Figure 4).

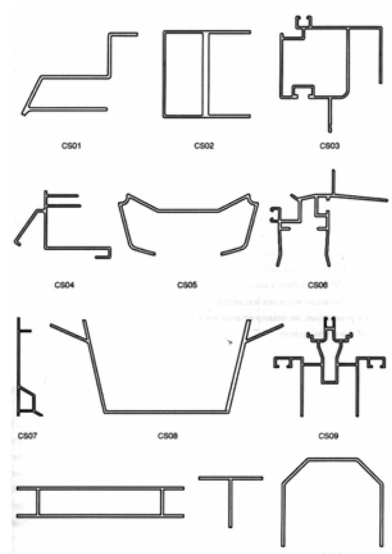


Figure 8 Aluminum extrusions tested by Mennink (2002) (Mennink used the PI's program to perform stability analysis of these extrusions)

B5 Advancing… Advanced Analysis

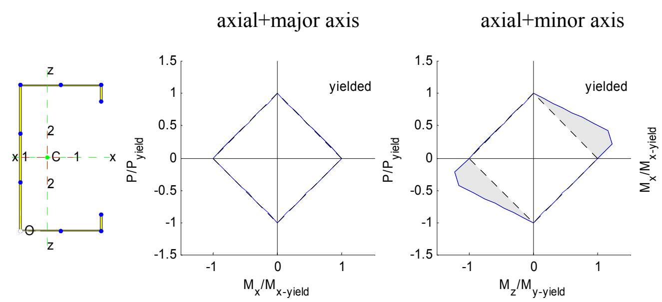
The robustness of advanced analysis will be improved if designers can add the flexibility of employing noncompact and slender cross-sections in their structural models, and know that the cross-section instability behavior is captured. Advanced analysis is the application of material and geometric nonlinear analysis for the design of steel frames (e.g., Chen 1997, Liew et al. 1993, Ziemian et al. 1992 and others). In the long-term, advanced analysis aims to replace significant portions of the Specification. For example, the beam-column interaction equations would be replaced with cross-section analysis including yielding, residual stresses, and imperfections, all integrated within a frame analysis. To date, advanced analysis typically ignores noncompact sections (e.g., Kim and Chen 1996) primarily because beam elements employing plastic hinges, or fiber elements, are ill-suited for local buckling phenomena.

However, the need is real: "local buckling is a very crucial element to be considered in second-order plastic hinge analysis" (Kim at al. 2003). A number of benchmark solutions have been prepared, including full-scale shell element models (Avery and Mahendran 2000) as well as experiments on 3D two-story single-bay frames consisting of non-compact sections (Kim and Kang 2004). Initial attempts to modify current advanced analysis tools have been made, for example empirical rules based on Specification compactness (λ) limits have been used to soften plastic hinge models (Kim and Lee 2001, Kim et al. 2003), or fiber element stress-strain relations have been empirically softened to reflect observed local buckling behavior (Huang et al. 2004).

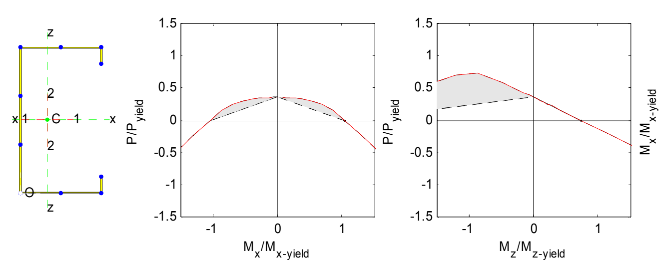
Existing methods suffer from being closely tied to current cross-sections, and do not provide a general approach. What is proposed here is that a unique cross-section stability analysis conducted for the actual applied P, M_x, M_y should be conducted, either in-line with the analysis (in a multi-step solution), or developed before the analysis to create an appropriate "buckling surface" to account for cross-section instability. The DSM methods proven successful for beams and columns should be extended to beam-columns and incorporated into analysis. DSM work on beam-columns represents an exciting area with great potential return. The PI has an NSF proposal (see Section I) to examine DSM for cold-formed steel beam-columns. This proposal would extend the application to structural steel shapes and examine integrating the method into advanced analysis.

The most obvious (and flawed) means for extension of DSM to beam-columns is the extrapolation of interaction equations:

$$\frac{P_{demand}}{P_{capacity}} + \frac{M_{x-demand}}{M_{x-capacity}} + \frac{M_{y-demand}}{M_{y-capacity}} \le 1.0 \quad (4)$$



(a) first yield (shaded areas indicate conservative error in the use of a linear interaction equation for first yield)



(b) local buckling (shaded areas indicate conservative error in the use of a linear interaction equation for local buckling)

Figure 9 Linear interaction diagrams for a channel
(Assuming restrained bending about *x* and *z* axes.)

$P_{capacity}$ and $M_{capacity}$ could be replaced by appropriate DSM predictions for isolated beams and columns, such an approach is simplistic and overly conservative. Even for the prediction of first-yield Eq. 4 is only adequate for doubly-symmetric sections, e.g., consider axial+minor axis bending of a channel as given in Figure 9a. More importantly, cross-section stability cannot be adequately predicted by simple interaction equations as shown with local buckling of a channel in minor-axis bending (Figure 9b). If the bending adds compressive stress to the flange tips the compression capacity is driven down, but if the bending relieves the compressive stress on the flange tips the compression capacity increases!

A proposed extension of DSM to beam-columns is illustrated in Figure 10. Applied actions P and M are expressed as a P/P_y, M/M_y demand pair, where P_y and M_y are the isolated column squash load and beam yield moment. P/P_y, M/M_y determines the angle θ in the interaction space of Figure 10. Yielding is unique to the section and occurs a distance $\lambda_y(\theta)$ from the origin. Local buckling is unique to the section and occurs at $\lambda_{cr}(\theta)$ from the origin. Interaction takes the form:

$$\sqrt{(P/P_y)^2 + (M/M_y)^2} \le \lambda_n \text{ where } \lambda_n = f(\lambda_{cr}, \lambda_y) \qquad (5)$$

Development of λ_n is a critical need for all buckling modes, but expressions for isolated beams and columns are known, a possible extension to Eq. 2 would be:

$$\lambda_n = \left(1 - 0.15\left(\frac{\lambda_{cr}}{\lambda_y}\right)^{0.4}\right)\left(\frac{\lambda_{cr}}{\lambda_y}\right)^{0.4}\lambda_y \;\forall\; \sqrt{\frac{\lambda_{cr}}{\lambda_y}} > 0.776 \qquad (6)$$

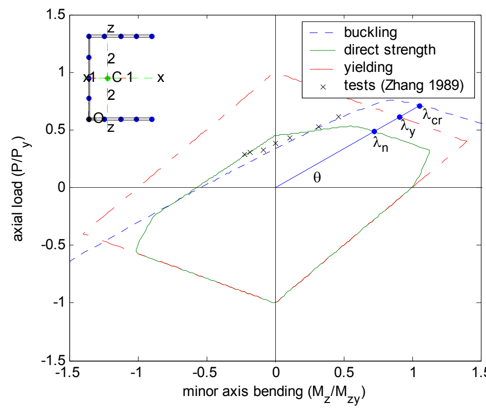


Figure 10 DSM applied to a beam-column

The proposed method provides an approach for beam-column interaction readily extendable to the more general case of P,M_x,M_y triplets, as described further in Schafer (2003). Hancock (2004) applied the basic methodology to a limited set of cold-formed steel channels with good success. The PI is working to develop and verify a DSM methodology along the lines of Figure 10 for cold-formed steel beam-columns. The plan includes extensive testing and nonlinear FEA with shell elements to fully investigate (*a*) the wide variety of cold-formed steel cross-sections, (*b*) any combination of P, M_x, M_y loading including load path dependency, (*c*) end conditions, including simulated field conditions, and (*d*) all relevant limit states: local, distortional, global – and potential interactions.

To examine the extension of DSM to structural steel beam-columns the approach would be to (i) gather existing data and (ii) augment with additional computational studies using fully nonlinear FEA analysis with shell elements in ABAQUS (2004). Proposals to perform experimental testing would be developed subsequent to this work. In addition to developing a method for predicting the strength (i.e., Figure 10) the reduced stiffness of the sections must be incorporated. Such reductions have been developed for cold-formed steel beams, but have not been investigated in the context of beam-columns. The research would include all structural steel shapes, but have particular emphasis on sections which are not doubly symmetric, such as the C- L- and WT-Shapes. These sections are expected to see the biggest benefit from moving to the new approach. The inelastic regime (M_y<M<M_p) will also be of particular interest since cold-formed steel design limits capacity to M_y and sensitivity to the residual stress pattern and strain hardening regime will have its greatest impact here. Finally, it is proposed to initially implement the developed method in Ron Ziemian's program, MASTAN, so that others can explore the solution.

B6 Creating a consistent design methodology

One goal of the proposed research is to provide a consistent design methodology for thin-walled steel sections. For the cold-formed steel specification DSM was introduced as a supplementary design method, rather than replacing traditional methods. In the long term it is expected that DSM's ability to better handle element interaction, distortional buckling, and the design of optimized sections with multiple stiffeners, will make it the method of choice in cold-formed steel. To better understand the impact of using DSM in structural steel design two conceptual issues that DSM treats differently than the current AISC Specification are highlighted below: element interaction and local-global interaction.

B5.1 Element Interaction

Typically the design of members with slender elements has been tied to classical plate buckling solutions. As such, members are idealized as a composition of plates with known boundary conditions, and slenderness limits or effective widths are appropriately derived for each element. Element interaction, the necessity for equilibrium and compatibility between any two elements of a cross-section to be maintained, is often ignored or only included in an ad hoc manner in the AISC Specification. In White et al. (2004) the PI examined the elastic local buckling behavior in pure compression for all of the shapes in the AISC manual, see for example Figure 11. DSM would employ such solutions for strength prediction. The solutions show that element interaction could be significant in some cross-sections, and that the issue is of growing importance for higher strength steels. The analysis shown (Figure 11) is only for elastic buckling of W-Shapes, and does not cover the inelastic regime. A continued interest in ductility for seismic design (given fracture limit states have been avoided) has also kept questions surrounding web/flange interaction in the literature (e.g., Daali and Korol 1994). A consistent look at element interaction, with a focus on inelastic interaction and its application in the DSM framework, would be examined in this research.

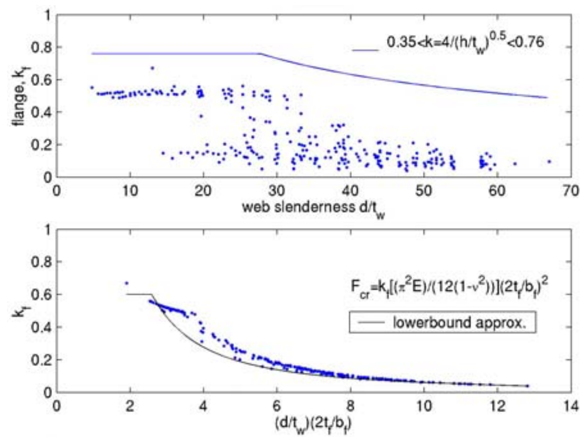


Figure 11 Local plate buckling coefficients for all W-Shapes in the AISC (2001) manual in pure compression, results based on elastic buckling finite strip analysis, for common W-Shapes used as columns the web is significantly more slender than the flange and reduces the flange k considerably.

B5.2 Q-factor approach to local-global interaction

The Q-factor approach has successfully provided reductions to account for local-global interaction in structural steel shapes for many years. The Q-factor modifies the long column curve in a manner originally developed for use in the cold-formed steel specification. However, subsequent to AISC's use the method was abandoned by the cold-formed steel specification in favor of the unified effective width method (Peköz 1987). The PI has performed extensive research on cold-formed steel columns (Schafer 2002) and was curious to see what the impact of using the currently employed AISC Q-factor approach would be on slender columns. The results, given in Figure 12 and detailed in White et al. (2004), are not promising. The Q-factor method is unconservative for slender cold-formed steel columns and systematically provides poor predictions for the most slender columns. The Q-factor approach fails to capture the correct trends in these highly slender columns.

This is not to say that the Q-factor approach fails us today, agreement on less slender hot-rolled steel tube columns appears reasonable (White et al. 2004). However, if structural steel shapes move towards more slender cross-sections by (a) embracing higher strength steels, or (b) through intentional shape optimization – existing methods such as the Q-factor approach will have to be re-examined.

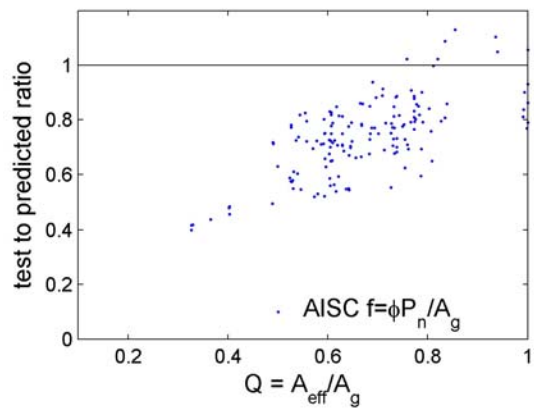


Figure 12 Test-to-predicted strength for cold-formed steel columns failing in local buckling if the current AISC Q-factor method was used in cold-formed steel design, AISC (2001) Q-factor method, NAS (2001) for effective width calculation with $f=\phi_c P_n/A_g$ to determine Q, 156 cold-formed steel column tests from Schafer (2002) local buckling only.

In cold-formed steel columns DSM (using formulas quite similar to Eq.'s 1-3) was shown to provide an adequate characterization of local-global column capacity without the use of effective width calculations, or iteration (Schafer 2002). The method is conceptually similar to the current cold-formed steel approach: the long column strength is determined without regard to local buckling, then the local buckling strength is determined, with the maximum strength limited to the inelastic long column strength. A similar approach is used for local-global interaction in beams. While these methods are approximate, they have been shown to work, and need to be explored further for structural steel shapes. As discussed previously, variations in cross-section thickness, multiple local buckling modes, and interest in the inelastic regime complicate the application of DSM to structural steel shapes. However, it is clear from Figure 12 and others that new ideas are needed to tackle issues such as local-global interaction if structural steel is to take advantage of higher yield strength steels.

C. Industry Impact

Can the structural steel industry take better advantage of the opportunities opened up by high performance and ultra high strength steels? Yes, of course numerous barriers exist, including the fact that higher strength steels lead to sections which are either (1) controlled by cross-section instability or (2) controlled by serviceability instead of strength. This proposal aims to address both of these issues by leveraging new research in cold-formed steel structures and extending the findings to hot-rolled steel. The anticipated results are a simplified and more robust design method that will enable designers to employ slender sections with ease, and an opening of new opportunities for manufacturers to re-think structural steel shapes and re-balance the serviceability vs. strength equation to take maximum advantage of higher yield strength steels.

The impact of this proposal is of a long-term nature, consistent with the goals of a young steel researcher who is planning for a lifetime of steel research (not just 4 years). The ideas are new, and in some cases quite different than the way we do things now, but much of the path has been cut, as the proposed design method has been shown to work in cold-formed steel and even formally adopted by the AISI Specification. Through the tireless backing of several members of the cold-formed steel Specification committee these ideas have come to light, and now have a chance to impact the cold-formed steel industry: new shapes, new products, higher strength steel, better designs. Steel wins when it embraces its technical advantages over competing products, and this proposal aims to provide that advantage to hot-rolled structural steel shapes.

D. Work plan and schedule

	Year 1	Year 2	Year 3	Year 4
	Fa Sp Su	Fa Sp Su	Fa Sp Su	Fa Sp Su
I. Evaluate the Direct Strength Method (DSM)	**Ph.D. Stud.**			
(Using DSM developed for cold-formed steel evaluate applicability to hot-rolled steel)				
Fully-braced beams and columns				
Perform FSM cross-section stability analysis for all AISC Manual shapes				
Predict strength based on current DSM expressions				
Compare with current AISC predictions and assess areas of greatest difference				
Beams				
Collect existing experimental data on compact, noncompact, and slender beams				
Perform FSM cross-section stability analysis				
Predict strength based on current DSM expressions				
Examine sources of error				
Columns				
following the same procedure as that established for beams				
Develop NSF grant for experimental complement to *I* and work in *II*.				
II. Extend DSM for beams and columns to hot-rolled steel shapes	**Ph.D. Student**			
Develop nonlinear FEA model (ABAQUS) to augment existing experimental data				
Inelastic regime (emphasis on beams)				
FEA parametric study of compact and noncompact beams				
develop simplified cross-section specific expressions for use in inelastic range				
Multiple local buckling modes				
identify common shapes with multiple local buckling modes (Figure 1c)				
perform nonlinear FEA analysis of shapes, focus on imperfection sensitivity				
develop modifications to DSM to account for multiple local modes as needed				
Additional issues				
use results of study I and FEA model to examine specific cross-sections which				
have DSM predictions that are different than conventional analysis, study:				
Element interaction				
Local-global interaction and Q-factor approach				
Any other sources of error identified in study I				
Provide modified/extended version of DSM for hot-rolled steel shapes				
III. Impact of high performance and ultra high strength steel on AISC Shapes	**M.S. Student #1**			
Model building study: strength vs. serviceability				
Select model buildings for typical span, load, cross-section				
Provide AISC predictions as yield stress is increased				
Provide DSM predictions as yield stress is increased				
Identify key differences and opportunities				
General parametric study: strength vs. serviceability				
Select broad class of standard members and loads				
Examine strength vs. serviceability for all members, loads, and Δ limits				
Identify opportunities where serviceability controls too early				
IV. Shape optimization			**M.S. Student #2**	
Determine current constraints (real and perceived) on shape optimization				
Use meetings and email to develop a dialog with manufacturers, contractors				
design engineers, and detailers to understand perceived constraints on				
changes to structural steel shapes				
Level 1 optimization: minor modifications				
Select sections from studies in III				
Keeping weight/foot and depth constant modify material distribution				
Demonstrate improvements in model buildings due to new shapes				
Level 2 optimization: new sections				
Demonstrate the potential for structural shapes beyond current practice				
V. DSM for beam-columns and integration into Advanced Analysis			**Ph.D. Student**	
Extension of DSM to hot-rolled steel beam-columns				
Using cold-formed steel method perform hot-rolled steel parametric study				
Collect available experimental data				
Develop nonlinear FEA model (ABAQUS) to augment existing experimental data				
Critically assess errors and integrate findings from work in *II*. above				
Integration into Advanced Analysis models				
Integrate cross-section stability analysis into MASTAN				
Augment plastic hinge model in MASTAN to include local stability reduction				

(yellow)	*Work to be completed by the PI*
(red)	*Work to be completed by the PI with a Ph.D. Student*
(blue)	*Work to be completed by the PI with a M.S. Student*
(green)	*Work to be completed by the PI with a M.S. Student*

Publications:

Journal Articles

Application to hot-rolled steel structures:

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Buonopane, S.G., Schafer, B.W. (2005). "Reliability Implications of Advanced Analysis in the Design of Steel Frames." ASCE, *Journal of Structural Engineering* (Submitted, see SSRC conference paper as well)

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Selected Recent Conference Papers

Application to hot-rolled steel structures:

†Schafer, B.W., Bajpai, P. (2004). "Stability Degradation and Redundancy in Damaged Structures." Annual Technical Session and Meeting, Structural Stability Research Council, April, 2004. Long Beach, CA.

Buonopane, S.G., Schafer, B.W., Igusa, T. (2003). "Reliability Implications of Advanced Analysis in Design of Steel Frames." Annual Technical Session and Meeting, Structural Stability Research Council, April, 2003. Baltimore, MD.

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Application to cold-formed steel structures:

Schafer, B.W., Ádány, S. (2005). "Understanding and classifying local, distortional and global buckling in open thin-walled members." Annual Technical Session and Meeting, Structural Stability Research Council, May, 2005. Montreal, Quebec, Canada.

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†Liu, H., Schafer, B.W., Igusa, T. (2004). "Cold-formed Steel Member Cross-section Shape Optimization by Knowledge-Based Global Optimization Method." American Society of Civil Engineering, Structures Congress, Nashville, TN.

†Schafer, B.W. (2003). "Coming Soon: A Simpler, Faster, Cold-Formed Steel Design." American Society of Civil Engineers, Structures Congress, Seattle, WA.

†Schafer, B.W. (2003). "Cold-Formed Steel Design by the Direct Strength Method: Bye-Bye Effective Width." Annual Technical Session and Meeting, Structural Stability Research Council, April, 2003. Baltimore, MD.

†Schafer, B.W. (2003). "Advances in Direct Strength Design of Thin-Walled Members." Advances in Structures: Steel, Concrete, Composite and Aluminum - ASSCCA'03, Sydney, Australia, June 23 - 25, 2003

†Schafer, B.W., Trestain, T. (2002). "Interim Design Rules for Flexure in Cold-Formed Steel Webs." 16th International Specialty Conference on Cold-Formed Steel Structures, Orlando, FL

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†Schafer, B.W. (2002). "Stiffened Elements with Multiple Intermediate Stiffeners and Edge Stiffened Elements with Intermediate Stiffeners: An All New B5." 16th International Specialty Conference on Cold-Formed Steel Structures, Orlando, FL

†Schafer, B.W. (2002). "Analysis of Sheathed Cold-Formed Steel Wall Studs." 16th International Specialty Conference on Cold-Formed Steel Structures, Orlando, FL

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Graham-Brady, L., Schafer, B.W., Li, J. (2003). "Analysis of Post-Buckling Behavior of Beam-Column Structures via Stochastic Finite Elements." Annual ASCE-Engineering Mechanics Division meeting, Seattle, WA.

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†Presented by Schafer at conference.

H. Facilities and Equipment

Laboratory:

The Department of Civil Engineering maintains a structural testing laboratory in the building. One full-time technician and one half-time machinist support the experimental work in the department. The structural laboratory is approximately 20 ft x 40 ft in plan and has a 20 ft. ceiling. The laboratory includes regularly spaced floor tie-downs, an electric over head crane, and a large adaptable reaction frame consisting of heavy hot-rolled steel sections. Additionally, the laboratory includes sinks, gas and vacuum lines, and is served by an MTS hydraulic pump for running either of the 2,000 lbf or 20,000 lbf actuators or one 100,000 lbf universal testing machine – all controlled by the same MTS 407 controller. An adjoining laboratory of approximately the same size includes an additional 8,000 lbf hydraulic universal testing machine for dynamic testing, and a 10,000 lbf screw-driven universal testing machine – all available for use in this proposal. Laboratory sensors include, load cells, LVDTs, position transducers, extensometers, accelerometers and other sensors. Data acquisition capabilities include 3 computers with National Instruments A/D boards, 1 laptop with an A/D PCMCIA card, and a National Instruments SCXI system for conditioning and reading strain gauges, LVDTs, accelerometers and 20 other analog channels along with LabView. Miscellaneous supporting equipment for field instrumentation is also available. In addition, the department was recently donated 10 Parker Series 2HX Actuators with 42 in. stroke, along with 2 enclosed pumps which can be used in the development of unique testing rigs. *The PI has experience using all of this equipment in his research efforts to date.*

Computational:

Computing resources at Johns Hopkins University are nearly completely de-centralized. Limited computer facilities are available for instructional purposes. Computers in current use in the PI's research group were purchased through startup funds and other grants. All of my current graduate students have Dell workstation class Intel machines varying from 1 to 2 years old. In addition I have 2 machines used primarily for finite element analysis with ABAQUS; the first is a 2 GHz Dell workstation with 2GB of memory, the second is a 3 GHz Dell workstation with 2 GB of memory both running Linux. Three computers with A/D boards and 1 laptop have also been purchased to support efforts in the lab. These resources will be available to support the research and educational initiatives proposed herein.

Office/Staff

The Department of Civil Engineering has two full-time administrative staff which are available for help on an as-needed basis. The Department of Civil Engineering has a full-time lab technician available to support any experimental testing proposed herein. Additionally the department has a part-time staff member in the machine shop available to aid in the manufacturing of fixtures and specimens. The Department of Civil Engineering shares an on site machine and wood shop with Mechanical Engineering.

I. Complementary Funding

No direct matching funds are related to the success of this proposal. However, the PI would use the award to (1) extend activities in existing and pending projects to have direct applicability to the needs of the hot-rolled steel construction and design community, and (2) initiate new proposals where hot-rolled steel construction and design, specifically related to cross-section stability and the use of ultra high strength steel, is the primary focus of the research.

In the past the PI has secured research funding and/or in-kind donations and fellowships from the

- National Science Foundation (NSF) ,
- American Iron and Steel Institute (AISI),
- Steel Stud Manufacturers Association (SSMA), and the
- Metal Building Manufacturers Association (MBMA).

Proposals to these organizations would be used to further leverage the AISC Faculty Fellow funding.

The research proposed herein would be complementary to a pending proposal with NSF: CAREER: Structural Stability and Thin-walled Structures. This 5 year project was ranked 1st in its panel review and NSF has informed the PI that funding should be available once the '05 budget is finalized. The research proposed in this proposal consists of (a) formalizing methods to classify instabilities in open cross-section thin-walled members, (b) extending the applicability of the Direct Strength Method for cold-formed steel members to members with holes and beam-columns, as well as, (c) a serious educational outreach effort related to structural stability. The AISC Faculty Fellowship funding would be used, in part, to extend the findings of this research to hot-rolled steel cross-sections. The funding would allow for students to be dedicated to research efforts in hot-rolled steel. (A copy of the proposal can be made available to reviewers, email schafer@jhu.edu. The relevant program officer at NSF is Steve McCabe, who can be contacted for the current status of the proposal, if needed, email smccabe@nsf.gov.)

The research proposed herein would be complementary to a pending proposal with AISI: Direct Strength Method for the Design of Perforated Members. This small proposal is investigating the best way to incorporate the design for holes (due to service access, etc.) in thin-walled locally unstable cross-sections. For cold-formed steel sections this issue is obviously of greater concern than in hot-rolled sections; however, access for services is always an important construction issue and methods that formally, accurately, and *easily* consider the increased potential for cross-section instability in such cases could be of great use. This project would be leveraged to consider extension of the ideas developed for cold-formed steel to hot-rolled and built-up steel sections with holes.

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L. Discussion of Selection Criteria

The following is a brief discussion of how the Institution, Principal Investigator and Proposed research meet the selection criteria outlined in the *Program Description* provided by AISC.

A. *Institution*

a. *Eligibility (see "Application");*

JHU provides an ABET accredited undergraduate degree in civil engineering, as well as MS and PhD degrees with concentration in structural engineering/ structural mechanics.

b. *proposed project constitutes a significant proportional increase in research related to structural steel being conducted at the institution;*

Traditionally JHU has conducted research in steel structures, primarily by Bruce Ellingwood. Bruce left JHU in the summer of 2000, the same time that I joined the faculty here. Since that time I am the only researcher with an active interest in structural steel behavior and design. My work has primarily focused on cold-formed steel structures and this fellowship would take my efforts in structural steel from an initially small level to four sustained years of active hot-rolled steel research.

c. *adequate resources to accomplish the proposed research;*

While JHU is a small private school, lacking in some of the large-scale experimental facilities found at other institutions, I have nonetheless found it possible to perform high quality research here. Targeted testing is possible, due in large part to having a full-time technician with significant field experience (he worked with Nick Jones on long span bridge testing for years) available. In addition, I have operated an extensive computational program since coming to JHU.

d. *active and effective instructional programs at both undergraduate and graduate levels in the disciplines pertinent to the proposed research.*

JHU has a small, but of consistently high quality, undergraduate civil engineering program – and a nearly equally sized graduate program. (Approximately 50 undergraduates and 40 graduate students.) Design of steel structures is required at the undergraduate level, and I teach this course. I also teach at the graduate level, where, structural stability and structural dynamics have been the courses where I have interjected topics relevant to modern structural steel behavior and design. We do offer a course in advanced steel design, typically taught by an adjunct. The strength of the JHU graduate program is the doctoral program, nearly all students are enrolled as PhD students, where the emphasis is primarily on structural mechanics with extensive treatment of stochastic mechanics.

B. *Principal Investigator*

a. *eligible (see "Eligibility of Candidates");*

I am currently in a tenure-track position at JHU, without tenure.

b. *previous experience and education, especially related to steel;*

My past experience and education are detailed in Section F: Resume. I hold a B.S.E from the University of Iowa and an M.S. and Ph.D. from Cornell

University. At Cornell I completed a thesis related to modeling and design of cold-formed steel. I was an Instructor at Cornell for one year, then went into private practice at the structural engineering firm of Simpson Gumpertz & Heger, Inc., for two years. In the summer of 2000 I joined the faculty at JHU.

c. *recent and current research, especially related to steel;*

   My recent journal publications and conference papers are broken down by subject area and detailed in Section F: Resume. I have been leading a multi-year experimental and analytical effort to put forth a more rational design methodology for thin-walled steel members, that better embraces current computational capabilities, while still recognizing the limits of our new tools. This effort reached its first major milestone in 2004 when the Direct Strength Method was adopted as Appendix 1 in the North American Specification for the Design of Cold-Formed Steel Structures. Significant work on the Direct Strength Method remains, including buckling mode classification techniques, beam-column design, and members with holes – all of which are topics of current research and interest. For hot-rolled steel structures, recently, I have focused on two topics: efficient estimates of structural strength for severe unforeseen hazards, and system reliability of steel frames designed using newly adopted advanced analysis methods – both topics, I believe, are of immense importance for the future.

d. *recent and current teaching activity, especially related to steel.*

   At JHU I teach a number of courses that have significant content related to steel structures. Perspectives on the Evolution of Structures provides a historical examination (post-Industrial revolution) of structural engineering – and the impact of steel is highlighted over the course of several lectures. I also teach a more traditional undergraduate Design of Steel Structures course, as well as graduate courses in Structural Stability, and Structural Dynamics. In addition, my educational outreach extends beyond JHU, through involvement and leadership roles with several service organizations including ASCE-SEI, SSRC, and others, as detailed in Section F: Resume.

C. *Proposed research*

a. *level of graduate student participation;*

   A budget and research plan has been created involving one PhD student and two MS students as requested in the program description.

b. *anticipated quality of the proposed investigation;*

   [for the committee to decide.]

c. *complementary funding from industry or government;*

   As detailed in Section I, this research will complement existing efforts with NSF and AISI, as well as be used to provide seed funding for additional proposals.

d. *level of cooperation likely from industry;*

   The basic ideas of this proposal have only been discussed with a few in industry; however, the potential benefits are significant for all in the structural steel marketplace. A key component of the proposal is taking the necessary steps so that the industry can leverage new abilities in manufacturing, both higher strength steels and the potential to create more optimized sections, with a goal of improving steel construction.

e. *relevance and potential usefulness of the research results to steel construction;*

The benefits of the research are discussed further in Section C. The envisioned benefits are not short-term, but rather represent the establishment of a sustained initiative to take better advantage of modern steel's most changing attribute: higher yield strength. By embracing the design of slender high strength steel sections and re-balancing the strength vs. serviceability equation steel construction can potentially be lighter, stiffer, and stronger.

f. *feasibility of the work plan and adequacy of resources;*

The work plan is detailed in Section D and the resources at JHU in Section H.

g. *realistic budget;*

To help contain the budget the research will leverage existing research projects and facilities, as well as focus on analytical and computational efforts as opposed to testing.

h. *probability that steel research will continue after termination of the project.*

The PI has a strong record in steel research and is serious about making long-term impacts in steel design, construction, and research.