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# A Stability Journey - Diaphragms, Cold-formed Steel and the SSRC

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**Abstract**

The presentation will cover steel and steel-composite diaphragm behavior, strength and design. Highlights of past projects, as well as an ongoing research project focused on diaphragm behavior and behavior of lateral frames as influenced by the diaphragms, will be presented. Additionally, highlights from cold-formed steel projects (strut purlins, component and full truss testing and analysis, steel deck web-crippling testing and analysis) with which the author has been involved will be reviewed. Finally, the "stability" of the Structural Stability Research Council (SSRC) during the time the author has been involved in the leadership will be reviewed.

## 1. Motivation for my journey

My own journey with structural stability, and coincidentally the SSRC, began in the academic year of 1982-83. I had the good fortune to take a graduate class at West Virginia University (WVU) from Professor Larry Luttrell entitled Structural Members and Frames. The course covered a variety of stability topics and was both challenging and invigorating. Professor Luttrell taught the course in a way that encouraged students to dig into the literature, not just sit and listen to lectures and work on outside class assignments. It was during this course that I developed a passion for research, spending hours in the library reading many articles and books on topics that were introduced in class. I also read my first papers by giants in the field such as Galambos, Yura, Winter, Beedle, Johnston and many others. I was first exposed to the *Guide to Stability Design Criteria for Metal Structures* (Johnston 1976), and *Structural Members and Frames* (Galambos 1968), both of which have been profoundly impactful to the subject matter during the course at WVU.

Sometime in the fall of 1982 or spring of 1983, I received a conference advertising announcement in the mail from the SSRC. The announcement was for the Third International Colloquium – Stability of Metal Structures that was held in Toronto in May of 1983. I was excited about the opportunity to attend the conference. Toronto was a reasonable drive from Morgantown, WV and I was able to convince a couple of my classmates that we should attend the conference. I still remember being in awe as many, if not most, of the key researchers, academics and practitioners working in the field of structural stability were in attendance. There were approximately 135 people in attendance from around the world. (SSRC 1983.) This was the

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very first professional conference that I attended and as I look back over 35 years, it was a wonderful way to start!

There were other mentors and influential connections along the way, but I will not go further describing those at this point. I will include a number of others in the acknowledgement section of the paper. My sincere hope is that this paper and ensuing discussion at the upcoming Annual Stability Conference (ASC) will be an inspiration, even if only a small one, to current students as they begin their own journey. I look forward to watching the new generation of contributors to the SSRC specifically and the field of structural stability in general as my own journey continues.

## 2. Diaphragms – the glue that binds

Floor diaphragms in steel-framed buildings typically consist of steel-concrete composite slabs constructed by placing concrete on steel deck. Roof diaphragms are typically steel deck without concrete fill. The in-plane stability of composite floor diaphragms and typical roof diaphragms is not generally a concern. That said, roof diaphragms are being designed in new and different ways, thus the in-plane stability is more often considered than in the past. Provisions exist in the diaphragm design standard (AISI 2016) for roof diaphragms to assess the in-plane stability. Provisions are not included, as they are not needed, for the stability of composite floor diaphragms.

Thus, while not typically being considered in the context of member "stability," floor and roof diaphragms are however critical elements of the lateral load resisting system. They are therefore considered an integral part of the design for strength and stability of steel frames. The work with which I have been involved the most focuses on the strength and stiffness of floor and roof diaphragms, but not on their role in the overall stability of frames. I am fortunate to be participating in a current research project that is comprehensive in that the behavior of diaphragm components, as well as the overall behavior of building frames, are being considered. The sections below will review both past and on-going work.

### *2.1 Previous work*

My early exposure to steel deck diaphragms was while a part-time lab assistant in graduate school at WVU. Being able to observe tests of various configurations of steel deck diaphragms began my fascination with cold-formed steel. Warping of the ends of the deck sheet, and how that behavior could be affected by very minimal added restraint, say from closure angles, and in turn how that restraint affected diaphragm behavior was fascinating to observe. It was also this work, along with other projects related to composite construction being conducted at WVU that led me to go to Iowa State University (ISU) for my doctoral studies.

I was fortunate to join a research project team at ISU under the direction of Professor Max Porter. The project was focused on strength and behavior of steel deck and concrete composite diaphragms. The two phases of the research program (Porter and Greimann 1980; Porter and Easterling 1988) included 32 full-scale composite diaphragms and constitute the largest number of composite diaphragms conducted to date (O'Brien 2017; O'Brien, et al 2017.) A schematic of the test frame for the ISU tests is shown in Fig. 1. The results of the ISU work (Easterling and Porter 1994a and 1994b) have indirectly and directly guided the evaluation and design of composite diaphragms for the past 30 years and are reflected in current design documents (AISI 2016; Luttrell et al 2015; Sabelli et al 2011)

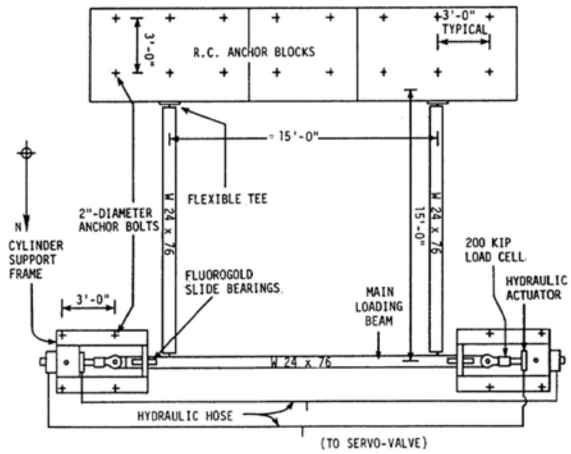

Figure 1. ISU Diaphragm Test Frame Schematic (Porter and Greimann 1980)

The ISU research programs resulted in the development of strength and stiffness determination procedures. Three strength limit states were identified and independent expressions for each were determined. These included diagonal tension limit of the composite slab, edge connector limit, and shear transfer mechanism limit. A multiple component diaphragm stiffness calculation was also developed. As with most research projects, if one looks back some years later, there are things that the team would do differently.  This is the case with the composite diaphragm work with which I was involved at ISU. The shear transfer mechanism limit received too much attention during the project as it is a limit state that does not need to be considered for typical design configurations. Thus, the diagonal tension and edge connector limit states should govern design provisions. Recommendations for changes to the AISI (2016) diaphragm design provisions are currently under consideration.  These reflect a fresh look at the ISU data and are informed by ongoing work described in the next section.

A variety of other steel deck diaphragm projects were conducted at Virginia Tech during the past 30 years. These include those reported by Avci, et al (2004 and 2016), Bagwell and Easterling (2008), Lease and Easterling (2006), as well as other proprietary studies. The collective work on diaphragms has continued to both contribute to the body of knowledge as well as drive my own curiosity.

*2.3 Ongoing opportunities*

The Steel Diaphragm Innovation Initiative (SDII) is a multi-year industry-academic partnership to advance the seismic performance of steel floor and roof diaphragms utilized in steel buildings through better understanding of diaphragm-structure interaction, new design approaches, and new three-dimensional modeling tools that provided enhanced capabilities to designers utilizing steel diaphragms in their building systems. This work is being conducted as a collaboration by researchers at Johns Hopkins University, Northeastern University, Virginia Tech and Walter P. Moore and Associates. The work is being funded as a collaborative effort by the American Institute of Steel Construction, the American Iron and Steel Institute, the Metal Building Manufacturers Association, the Steel Deck Institute and the Steel Joist Institute. Oversight for the project is conducted under the auspices of the Cold-Formed Steel Research Consortium, which is based at Johns Hopkins University.

Recent research results from work at Virginia Tech have been reported by O'Brien (2018), Qayyum, et al (2018) and Shi, et al (2018.) The project results, including presentations, reports, papers, etc are regularly updated and can be found at www.steeli.org.

## 3. Cold-formed steel components and members

I have had the good fortune to be involved with several projects related to cold-formed steel and stability. These have included early work on the subject of purlin supported roof systems in which the purlins were subjected to a combination of axial load and bending, so-called "strut purlins." We had the opportunity to engage in work on evaluation steel deck cross-sections for the limit state of web crippling. One of the projects that was particularly enjoyable to work on involved cold-formed steel trusses using complex hat shapes for the chord members. Each of these three topics are briefly highlighted below.

### *3.1 Strut-purlins*

Purlin supported roof systems consisting of C- or Z-shaped purlins with cold-formed steel roof deck are very common for single story pre-engineered metal buildings. Certain purlins are part of the lateral load resisting system. These tend to be located along the side wall between the end wall and the first braced bay. Combined axial and flexural forces need to be considered. The most critical load consideration may often be axial load and uplift due to wind loading. Prior to the work reported by Hatch (1990) and Hatch, et al (1990), there were no studies identified in the literature on similar members. The test configuration used is shown in Fig. 2 below. Note that the roof is built upside down in the vacuum chamber so that axial force could be applied to the purlin, while the vacuum was drawn from below the roof deck to simulate uplift on member. The results of the tests were compared with interaction equations in the AISI standard (AISI 1986) and the findings indicated that the AISI equations were conservative, but reasonably so, and thus could be used for strut-purlins.

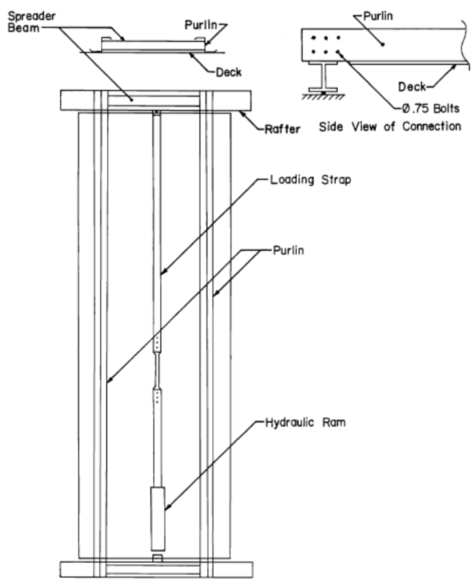


Figure 2. Strut-purlin Experimental Setup (Hatch, et al 1991)

*3.2 Web-crippling*
Results from two test programs that focused on web-crippling of steel deck profiles were reported on by Avci and Easterling (2002 and 2004.) These programs considered deck profiles subjected to end one flange loading. The study focused on the effects of fastening the deck profiles to the supporting member and compared results between fastened and unfastened cases. The fastened cases result in higher strengths and are likewise more typical of field construction. New web crippling coefficients for use in subsequent editions of the AISI specification (2001) were developed, but ultimately not adopted in favor of other research results.

*3.3 Truss components and full-scale truss testing*

A multi-year project on cold-formed steel roof truss systems constructed using complex hat shape members for both top and bottom chord elements was conducted at Virginia Tech (Nuttayasakul 2005; Nuttayasakul and Easterling 2003a, 2003b, 2004, 2006.) The results of flexural tests of complex hat shape members were included. In addition, stub column tests of nested C-sections used as web members and full-scale cold-formed steel roof truss tests were part of the study. In addition to the experimental work, numerical analyses using finite strip and finite element procedures were developed for the complex hat shape chord member in bending to compare with experimental results. Both elastic buckling and inelastic post-buckling finite element analyses were performed. A parametric study was also conducted to investigate the factors that affect the ultimate strength behavior of a particular complex hat shape. The full-scale truss testing setup is shown in Fig. 3.


Figure 3. Full-scale truss experimental setup

As reported by Nuttayasakul (2005) *"The experimental results and numerical analyses confirmed that modifications to the 2001 North American Specification are necessary to better predict the flexural strength of complex hat shape members, especially those members subjected to distortional buckling. Either finite strip or finite element analysis can be used to better predict the flexural strength of complex hat shape members. Better understanding of the flexural behavior of these complex hat shapes is necessary to obtain efficient, safe design of a truss system."*

## 4. The Stability of the SSRC

I joined the SSRC in 1991 as a Member-at-Large and became active with Task Group 13 – Thin-walled metal construction. In July 2000, I was invited to join the Executive Committee and I was thrilled to accept. I served in leadership roles for SSRC as Vice-chair from 2002-2006, Chair from 2006-2009, and Immediate Past-chair from 2009-2012. I note these dates and positions because the period of time that I have been involved with SSRC has been one of tremendous change for the organization. The SSRC has been a very stable organization for most of the 75 years following the founding. However, there were a few rather turbulent years when an objective observer would have viewed the organization in a relatively unstable position, indeed teetering on collapse. I have chosen to include this discussion so our members, particularly relatively new members, are aware of our history and most importantly that we continue to appreciate those that guided the organization through the challenging times.

### *4.1 Founding through the late 1990's*

The Column Research Council was founded in 1944 and the first meeting was held in September 1945. The Column Research Council would be renamed the Structural Stability Research Council 1976 due to the expanded scope of activity and interest (Sherman and Beedle 1994.) The concept of and need for the organization was first articulated in 1941 by Mr. Jonathan Jones, who at the time held the position of Chief Engineer at Bethlehem Steel. However, it was not until two years later that attention returned to Jones' idea (Wildt 1994.) Headquarters for the SSRC was not in a definitive location until 1966, when it was located at Lehigh University. Prior to that time, SSRC had no formal headquarters. The history of SSRC through 1994 is described by Johnston (1981), Wildt (1994), and Sherman and Beedle (1994.) A summary of activities – past, present and future – is provided by Easterling and Ziemian (2006.)

The mission of the SSRC has remained fundamentally unchanged for some time, and certainly since before the 1994 paper by Sherman and Beedle. The mission statement can be found at http://www.ssrcweb.org/mission/. As Sherman and Beedle note, the objectives, or mission, changed between 1944 and 1994 in large part to broadening focus and moving beyond some of the initial objectives.

It is fair to say that the first 50 years of the SSRC saw significant growth and contributions to the field of structural stability for metal and steel-concrete composite structures. The organization was indeed "stable." There are no formal public records to pinpoint a specific date, but sometime in 1998 issues began to surface that challenged that stability.

### *4.2 SSRC Headquarters move to the University of Florida*

The particular reasons why the relationship between Lehigh University and the SSRC broke down are not important for this discussion. During late 1998 and early 1999, the decision was made that Lehigh would no longer continue to serve as the home for the SSRC Headquarters. The members of the Executive Committee were forced to deal with this rather sudden turn of events, which included losing access to significant funds that were being used to pay SSRC staff and operational costs. Over the period of a few months, various alternatives were considered and a decision to move the SSRC Headquarters Operation to the University of Florida was approved by the Executive Committee. Professor Duane Ellifritt graciously agreed to serve in the role of Faculty Liaison and was assisted by Ms. Diana Walsh and Dr. Perry Green who moved to

Florida from Lehigh. Following Dr. Ellifritt's retirement, Dr. Green assumed the responsibilities of Faculty Liaison. Ms. Walsh left the SSRC and returned to Pennsylvania. Ms. Christine Schwing became the administrative assistant for the SSRC. This group was instrumental in helping the SSRC navigate the immediate times following the departure from Lehigh.

A key operational change occurred with the relocation of the SSRC Headquarters to Florida. The 2001 SSRC ASC was held in conjunction with the American Institute of Steel Construction (AISC) North American Steel Construction Conference (NASCC.) This move turned out to be a proverbial "win-win" for AISC and SSRC. The two organizations have collaborated in offering the combined event since that first joint conference in 2001. The members of the Executive Committee at that time are to be applauded for making this happen. It would, in my opinion, prove to be the start of what would become the most significant collaboration for SSRC in the past 25 years, but more on this point later.

In 2002 and early 2003, challenges arose with the headquarters operation being housed at the University of Florida. Again, the specific details are not important for this discussion, but once again the Executive Committee found itself dealing with several issues that seriously jeopardized the future existence of the SSRC. Dr. Green was very ably continuing to serve the SSRC while trying to navigate the existence of an organization not firmly attached to the University of Florida. These issues were compounded by the part-time administrative assistant not being located on campus and on the university payroll.

Given the challenges that had arisen, a new operational model was required. The Executive Committee discussed whether it was wise going forward to continue having the SSRC Headquarters located at a university. Other alternatives were discussed, but ultimately two proposals were solicited from universities that were deemed to be viable alternatives. At the April 2003 Executive Committee meeting, a proposal from the University of Missouri – Rolla was accepted and the SSRC Headquarters was relocated.

*4.3 SSRC Headquarters move to the University of Missouri-Rolla - now the Missouri University of Science and Technology (MST)*

Professor Roger LaBoube assumed the position of Faculty Liaison upon the move of SSRC Headquarters to MST in 2003. Ms. Christina Stratman served as the SSRC administrative assistant. Both Dr. LaBoube and Ms. Stratman provided high quality professional service to the SSRC. They enabled a smooth transition for headquarters operations to MST. A big part of the success with the SSRC Headquarters being located at MST was due to the experience that Professor LaBoube and Ms. Stratman had running a similar operation, the Wei-Wen Yu Center for Cold-formed Steel Structures (CCFSS.) The CCFSS had similar attributes – conducted conferences with technical proceedings, sponsored continuing education short courses, and was administered with less than full-time staff. It was a great fit from the beginning.

The period from 2003-2013 was one of steady growth and a return to financial stability for the SSRC. The relationship with AISC continued to prosper. The collaboration between the ASC and the NASCC flourished, in large part because the SSRC papers provided a significant additional technical track of papers and presentations to the NASCC. Additionally, SSRC collaborated with AISC in the delivery of short courses that became an important part of the relationship.

The SSRC Executive Committee was cognizant that Dr. LaBoube would be retiring from full-time academic service. Thus, discussions ensued about the future of the SSRC Headquarters. The relationship with AISC had become so positive that a natural discussion occurred regarding the possible relocation within the AISC. SSRC Chair Ron Ziemian began discussions that would ultimately lead to the next phase of the SSRC story.

*4.4 SSRC collaboration with AISC*

The SSRC Headquarters operation moved to Chicago in 2013 and functions within the AISC administrative structure. A memorandum of understanding is in place that describes the functional relationship for operations, conference participation, short courses, etc. The SSRC has not been more stable or in a healthier financial position in the past 25 years. I am of the opinion that the willingness of AISC to collaborate with SSRC on the 2001 NASCC and ASC was the turning point. The added benefits related to short course delivery and the oversight of the headquarters operations will result in a bright future for decades to come.

**Acknowledgments**

I want to begin by expressing sincere gratitude to members of the SSRC Executive Committee for bestowing the honor of being the recipient of the 2019 Lynn S. Beedle Award. I am confident that there are a number of equally, if not more, deserving individuals. That said, I assure you that no one is any more appreciative or humbled by the award.

There are many individuals and organizations to thank as contributors to my journey. I began by recognizing Professor Luttrell at West Virginia University for first instilling excitement in me for the subject of structural stability. Professors Fred Graham and Lowell Greimann at Iowa State University continued where Professor Luttrell left off. They were wonderful faculty members and mentors. My journey as a faculty member at Virginia Tech was likewise supported by a number of wonderful colleagues. A special note of thanks is due to Professor Tom Murray for his help in guiding and supporting my journey within the steel community.

I am also indebted to a number of SSRC colleagues. The list is long and in the interest of brevity, and for fear of not recognizing someone, I am going to limit my acknowledgements. Reidar Bjorhovde was kind enough to facilitate my joining the Executive Committee during his time as Chair of the Executive Committee. This engagement led to great opportunities for me and I will always be indebted to Dr. Bjorhovde. Fellow members of the Executive Committee, including past and current chairs Don Sherman, Nestor Iwankiw, Ron Ziemian, Ben Schafer and Todd Helwig have shown remarkable leadership, moved the SSRC forward and deserve our collective thanks.

The research that I described was sponsored by a number of organizations, including the American Institute of Steel Construction, American Iron and Steel Institute, Consolidated Systems Inc., Metal Building Manufacturers Association, Metal Construction Association, National Science Foundation, Nucor Research and Development, Steel Deck Institute, Steel Joist Institute. Without the generosity of sponsors, very little of the needed work would be possible.

Finally, I want to acknowledge and pay tribute to Professor Lynn S. Beedle. I want to quote from the SSRC website, member society page, as I believe it is important to note some of Professor's accomplishments and those are nicely summarized, even if very briefly, on the website.

*"After graduation from the University of California at Berkeley, and a career in the US Navy during the Second World War, Lynn Beedle spent his entire professional life at Lehigh University in Bethlehem, PA. For many years he was director of the Fritz Engineering Laboratory which became world-famous during his tenure. For many of us the name Lehigh and Beedle are synonymous. Many of the experiments and theories of the strength and stability of steel structures that served as the basis for all modern steel design specifications in the world were performed and developed there under his leadership. His name is associated as a leader of three intellectual activities that dominated the structural steel engineering profession in the second half of the Twentieth Century: 1) plastic analysis and design; 2) the ultimate strength of axially loaded columns; and 3) tall building planning and design. Lynn Beedle joined the SSRC soon after its founding and he was one of the members who formulated the questions and provided the answers to the pressing stability concerns of the 1950's and 1960's. He served as technical secretary in the early years, he was chairman of the Council, and for many years he was its Director. He spent more than half his life nurturing and guiding the Council, acting as its spokesman here and abroad. Through his vision the SSRC is one of the most esteemed American structural engineering organizations in the world today."*

I had the great fortune of interacting with Professor Beedle both as a student at that very first SSRC conference I attended in 1983, as well as later when I became a member of the Executive Committee. My recollection is that he was just as approachable for a wide-eyed student as he was for colleagues on the Executive Committee.  It is hard to identify anyone that served the SSRC longer and at a higher level than Professor Beedle. The fact that the highest honor bestowed by the SSRC bears Professor Beedle's name is most appropriate.

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