Report of the NIST Workshop on Automated Steel Construction [1]

by

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ABSTRACT: The Building and Fire Research Laboratory of the National Institute of Standards and Technology, in cooperation with the American Institute of Steel Construction, sponsored a workshop on automated steel construction. The purpose of the workshop was to investigate the development of new technologies to facilitate automating the steel construction process. Desired outcomes included a clear definition of issues and constraints, the identification of candidate breakthrough technologies, and the development of a research roadmap. A description of the workshop structure, agenda, and preliminary results are presented.

KEYWORDS: construction automation, automated steel erection

1.0 INTRODUCTION

Productivity, reliability, and safety are the three predominant issues facing the steel construction industry today. In both industrial facilities and commercial buildings, hot-rolled steel members are typically joined together either by welding or using high strength bolts. These processes require a significant amount of skilled labor, and in the case of high-rise construction, constitute one of the most dangerous specialties in the already hazardous construction industry. Inspection is difficult and time consuming, and often, the connections are the weakest link in the resulting structure.

The steel construction industry faces significant challenges to remain competitive. The following two statements succinctly summarize the issue [1]:

> "The U.S. construction industry must begin to move away from a nearly exclusive labor-intensive business and towards automation to be competitive in the ever-shrinking global marketplace."

> "Decreasing fabrication and erection time for steel frame buildings, while increasing the safety of workmen during construction are issues that must be addressed, and provides the motivation for automated construction."

According to the American Institute of Steel Construction (AISC), a 25 % reduction in time required to erect a steel frame structure is needed. In response to this stated need, the NIST Building and Fire Research Laboratory (BFRL) and AISC co-sponsored a workshop on Automated Steel Construction at the NIST campus in Gaithersburg, MD on June 6 and 7, 2002. The workshop brought together steel producers, fabricators, designers, erectors, and construction automation experts to discuss factors affecting the steel construction industry and to identify possible courses of action to assist the industry. The desired outcome from

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the workshop was a clear definition of issues and constraints, identification of candidate breakthrough technologies, and the development of a research roadmap. This report presents information contained in the keynote addresses and results of the working group breakout sessions.

2.0 WORKSHOP FORMAT

The workshop convened over a period of 2 days, during which the participants discussed the challenges faced by the US steel construction industry and the various technologies that could be used or developed in order to meet those challenges.

There were a total of 17 non-NIST attendees at the workshop. Participants included representatives from 3 steel producers, 3 steel fabricators, 2 steel designers, and 6 steel erectors, as well as 3 construction robotics and automation researchers. NIST researchers included personnel from BFRL's Materials and Construction Research Division and the Manufacturing Engineering Laboratory's Intelligent Systems Division.

The workshop was divided into three sessions over a day and a half. Each session included a topical presentation[3], a breakout session, and a full group discussion.

3.0 DETAILED AGENDA

3.1 Day One

Day one began with an introduction by the NIST Construction Metrology and Automation group (CMAG) leader, Dr. William C. Stone.

The introduction was followed by a presentation by Dr. Carl T. Haas of The University of Texas at Austin entitled "Automation in Steel Erection" [2]. Dr. Haas' presentation included a definition of industry problems, possible opportunities for automation, and a review of some previous construction automation research and development activities. Specific opportunities for automation discussed included:

- Robotics and process integration in the fabrication shop
- Materials tracking using radio frequency identification (RFID) tags, bar codes, etc.
- Design of connections for compliant assembly
- Pre-assembly to minimize field connections
- Integrated project processes, databases, and 4-D models
- Positive control of members and subassemblies using manipulator arms, inverse Stewart platforms, etc.
- Automated welding, bolting, adhesion, etc.
- Global positioning and locating systems

Examples of previous applicable research and development presented included:

- Lehigh ATLSS connection [3]
- NIST RoboCrane [4]
- Japanese automated building systems [5,6,7]
- UT Large Scale Manipulator [8]

Following the first presentation, the workshop participants were divided into 4 groups. Each group was tasked with forming a list of technologies that could benefit the steel construction industry and a corresponding list of criteria that could be used to rank those technologies.

The lists of technologies from the 4 breakout groups were then presented to all the workshop participants and discussed. A single list of the most promising technologies and a single list of evaluation criteria for those technologies was then developed by the workshop participants. These lists are presented in Tables 1 and 2.

The afternoon session of day one began with a presentation by the president of National Riggers and Erectors, Inc. (Plymouth, MI), Mr. Robert Dunn, entitled "Steel Erection and Challenges" [9]. Mr. Dunn reviewed the challenges facing the steel industry including safety, quality, workforce aging, and the cost of construction.

[3]All workshop presentations available on the CMAG website: www.bfrl.nist.gov/861/CMAG/index.html

He then reviewed various elements of the erection process, presented a cost breakdown of those elements, and projected potential cost benefits of various process improvements. Mr. Dunn stated the areas with the greatest opportunity for potential cost savings include:

- Ground Operations (receiving, etc.)
- Hoisting
- Ground Assembly
- Temporary Bracing
- Detailing

In his conclusion, Mr. Dunn outlined the following 4 recommendations for application of automation to steel erection and the corresponding potential cost savings:

1. Pre-assembly and/or modularization of roof/floor/wall components can save 10 % to 20 % of ground operations/hoisting costs which constitutes 45 % of total erection cost – a 4.5 % to 9.0 % overall savings.
2. Optimizing crew sizes and using innovative lifting/storage devices can save 15 % to 20 % of hoisting cost which comprises 30 % of the total erection cost - a 4.5 % to 6.0 % overall savings.
3. Use of "snug-tight" bolts in bearing connections can realize savings of from 30 % to 35 % of this cost driver which accounts for 30 % of erection costs - a 9.0 % to 10.5 % overall savings.
4. Semi-automated welding practices can save 2 % to 5 % of overall erection cost.

Following Mr. Dunn's presentation, the workshop participants were again divided into 4 groups. Each group was tasked with forming a list of challenges that the US steel construction industry faces and a corresponding list of criteria that could be used to rank those challenges.

The lists of challenges from the 4 breakout groups were then presented to all the workshop participants and discussed. A single list of the most important challenges and a single list of evaluation criteria for those challenges was then developed by the workshop participants. These lists are presented in Tables 3 and 4.

Once the lists of technologies, challenges, and corresponding evaluation criteria were developed, each workshop participant was then asked to choose what they felt were the 5 most important technologies and the 5 most important challenges. The participants were then asked to rank their chosen technologies and challenges in terms of their relative importance to one another.

The participants were also asked to repeat the same process for the lists of criteria corresponding to the technologies and challenges; however, in this case the participants were asked to choose only three criteria from each list.

3.2 Day Two

Based on the ranking of the technologies and challenges (and their corresponding criteria from day one) day two of the workshop began with the participants scoring the top 5 technologies and challenges (and the top 3 criteria for each) using the Analytical Hierarchy Process (AHP), which is described in section 4.0.

The scoring process was followed by a presentation by Dr. Jim Ricles of Lehigh University (Bethlehem, PA) entitled "Next Generation Steel Structures." Dr. Ricles reviewed steel framing, structural requirements for connections, and current connection schemes. To establish the need for automated steel construction research, Dr. Ricles provided the following summary statements:

- Construction industry comprises approximately 8 % of the U.S. Gross National Product.
- U.S. construction productivity has shown an average annual net decrease of nearly 1.7 % since 1969.
- Procedures for erecting building structures have changed very little over the past 80 years (although rivets have been replaced by bolting and welding). Erectors perform strenuous tasks in a highly dangerous environment.

- Incidents of occupational injury reported for construction workers comprised over 10% of all cases.
- Workers' Compensation Insurance for steel workers is 19.3% of wages, the highest of all construction workers.
- Percentage of fatalities in the construction industry (limited to building erection) from falling is 43%.

Dr. Ricles then discussed required connection characteristics for automated construction and provided examples of connection ideas for automated construction. Characteristic features required of next-generation beam to column included [10]:

- *Self-alignment* – The connection must be able to guide the beam toward the proper location once contact is made between connection elements located on the beam and column.
- *Tolerances* – The connection must have tolerances which allow for misalignment or out-of-plumbness.
- *Adjustment* – Because of the tolerances that must be built in, it is unlikely that the connection will be precisely in its correct position after erection. Therefore, the connection must have the ability to be adjusted easily.
- *Stiffness, Strength and Stability* – The connection must be strong enough to carry erection loads while possessing a suitable amount of stiffness to control deflections. Furthermore, the connection must be stable enough to allow erection of the structure to continue until the final fastening.
- *Modularity* – The connection should be able to be mass-produced with a standard shop fitting operation and with quick, automatic erection capabilities.

Following the presentation, the workshop participants were once again divided into 4 groups. The purpose of the last breakout session of the workshop was to brainstorm ideas for new connection technologies for use in steel construction.

The ideas that resulted from the breakout sessions were then discussed among all the workshop participants. The primary feedback from the group centered on three needs. These included better production and fabrication processes to reduce tolerance requirements in the connector, the application of automated welding technologies - common in manufacturing - to steel erection, and machinery to eliminate or reduce the human involvement in the bolt-up process.

4.0 ANALYTICAL HIERARCHY PROCESS

The Analytical Hierarchy Process (AHP) is a multi-criteria (or multi-attribute) decision-making tool that was originally developed by Thomas L. Saaty in the early 1970's [11]. AHP is particularly useful when trying to rank alternatives based on the qualitative opinions of a group of experts. Since ranking the technologies and challenges that resulted from the workshop could not be carried out quantitatively without in-depth analyses, the opinions of the assembled steel industry experts were used with the AHP to rank the technologies and challenges.

The AHP is based on the pairwise comparison of the given alternatives taking only one criterion into consideration for each set of comparisons. Therefore, given n alternatives, the possible number of non-duplicative pairwise comparisons of the alternatives is

$$\sum_{i=1}^{n-1}(n-i)$$

If we are to rank these alternatives based on m criteria, then the above pairwise comparisons must be repeated m times (once for each criteria). For example, if n = 10 and m =5, then 225 comparisons would be required to complete the AHP! Hence, when using the AHP to rank several alternatives one must be careful to limit the number of alternatives and number of criteria in order to avoid an unwieldy number of comparisons. It was for this reason that the workshop participants were asked to choose only the top 5 technologies and challenges and only the top 3 criteria for each (resulting in a total of 60 comparisons).

The AHP also provides a means of checking the consistency of the pairwise comparisons so as to get a measure of the reliability of the data.

5.0 RESULTS

The results presented herein are limited to the results of the workshop's first two breakout sessions and the AHP analysis of those results.

5.1 Breakout Session One

The first breakout session resulted in a list of 12 technologies that the 17 workshop participants felt would be helpful in improving the productivity of steel construction. This session also resulted in a list of 10 criteria that the participants would use to rank the technologies. Tables 1 and 2 show the technologies and criteria, respectively, ranked in order of importance from top to bottom (based on the conglomeration of the participants' individual direct rankings).

5.2 Breakout Session Two

The second breakout session resulted in a list of 22 challenges that the 17 workshop participants felt the US steel construction industry currently faces. This session also resulted in a list of 9 criteria that the participants would use to rank the challenges. Tables 3 and 4 show the challenges and criteria, respectively, ranked in order of importance from top to bottom (based on the conglomeration of the participants' individual direct rankings).

5.3 AHP Results

In order to limit the number of pairwise comparisons conducted during the application of the AHP, only the top 5 technologies and challenges and the top 3 criteria were considered. For example, although in Table 2 the safety criterion ranked 4^{th} in importance, it was not selected for the AHP analysis for the above reason. Ideally the AHP analysis would be conducted with all the technologies and challenges and all of their corresponding criteria.

Tables 5 and 6 show the results of the AHP analysis for the technologies and challenges, respectively. Table 7 shows the number of valid responses from which Tables 5 and 6 were generated. The valid responses were chosen based on an acceptable consistency ratio calculated as part of the AHP analysis [2].

Comparing Tables 1 and 3 with Tables 5 and 6, respectively, shows that the AHP results agree closely with the results of the workshop participants' manual ranking of the technologies and challenges. The AHP analysis also shows that apart from the "Material tracking" and "Material handling" technologies in Table 5 the final weighted scores in Tables 5 and 6 are not sufficiently different from one another to produce clear winners.

6.0 CONCLUSIONS AND FUTURE WORK

The workshop participants responded positively to the potential introduction of new technologies to the steel construction process and agreed that automation was needed in the industry. Many attendees volunteered to support future site visits and pilot studies. Based on the workshop response, the American Institute of Steel Construction is forming a steering committee to guide future research and the NIST Construction Metrology and Automation Group is making this research area a primary focus. A recommended research roadmap for automating steel construction will be presented in a forthcoming publication. This publication will include further analysis of the workshop results followed up by site visits and interviews with industry experts.

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Table 1. List of Helpful/Desired Technologies.

Ranking	**Technology**
Most	New connector technology
Desired	3D/4D CAD and data interchange
	Automated welding
	Material tracking technology (logistics)
	Piece movement technology (material handling)
	Plumbness technology
	Simpler method for installing and tensioning bolted connections
	Technology to locate components and objects
	Technology to create as-built models
↓	New steel technology
Least	Jack-up construction technology
Desired	Deck-sheet sidelap fastening technologies

Table 2. List of Criteria for Ranking the Technologies.

Ranking	**Technology Criteria**
Most	Cost savings
Important	Quality
	Speed/productivity
	Safety
	Minimization of rework
	Ease of Use
↓	Durability
	Time until 100% ROI
Least	Tolerance accommodation
Important	Make task attractive to labor

Table 3. List of Challenges Faced by the US Construction Industry.

Ranking	**Challenges**
Most	Reduce overall time to construct
Important	Reduce time from design to erection
	Need to optimize man-hours/ton
	Connection technology
	Efficient supply chain management from shop to erected state
	Facilitate information exchange
	Maximize efficiency of hoisting equipment
	Minimize cost of moment connections
	Reducing number of pieces (design stage)

	Standardize perimeter framing
	Inspection is labor intensive, time consuming, etc
	Minimize fall risk
	Confirming foundation accuracy
	Optimize bolting process on current connections
	Shop drawing time reduction (project critical path)
	Changing mind-sets of engineers, designers, constructors, etc.
	Accurate installation of base detail
	Streamline the code acceptance process
	Expand ability to use prefab modules
	Determining actual location of piece in lay-down area
	Ability to coordinate multiple cranes
	Improve quality control (tighten tolerances) of steel members
Least Important	Erection process susceptible to weather restrictions

Table 4. List of Criteria for Ranking the Challenges.

Ranking	**Challenges Criteria**
Most Important	Overall cost benefits
	Safety
↓	Productivity
	Quality
	Size of market
	Non-proprietary
	Code acceptance possibilities
	Time to market acceptance
Least Important	Durability/performance of end product

Table 5. AHP Results for the Top 5 Technologies and Top 3 Criteria.

Criteria (weights) / **Technology.**	Quality (0.41)	Cost Savings (0.34)	Productivity (0.25)	Final Weighted Score
Connectors	0.20	0.27	0.27	**0.24**
3D/4D CAD and data interchange	0.25	0.21	0.21	**0.23**
Automated welding	0.26	0.17	0.22	**0.22**
Material handling	0.15	0.18	0.15	**0.16**
Material tracking	0.14	0.17	0.15	**0.15**

Table 6. AHP Results for the Top 5 Challenges and Top 3 Criteria.

Criteria (weights) / **Challenges**	Overall Cost Benefits (0.41)	Productivity (0.35)	Safety (0.24)	Final Weighted Score
Reduce time from design to erection	0.30	0.19	0.15	**0.22**
Connection technology	0.20	0.18	0.30	**0.21**
Reduce overall time to construct	0.17	0.24	0.20	**0.20**
Need to optimize man-hours/ton	0.14	0.23	0.17	**0.18**
Efficient supply chain management	0.20	0.17	0.17	**0.18**

Table 7. Number of Valid Responses for Each Pairwise Comparison.

Comparison of:	**Valid Responses**
Pairs of challenge ranking criteria	7
Challenge pairs vs. Overall cost benefits	10
Challenge pairs vs. Productivity	9
Challenge pairs vs. Safety	13
Pairs of technology ranking criteria	8
Technology pairs vs. Cost savings	14
Technology pairs vs. Quality	12
Technology pairs vs. Productivity	14