US Egypt Cooperative Research: Use of Cold-Formed Steel in Residential Housing

PROJECT DESCRIPTION

A Background
A.1 Motivation
The largest component of the world’s building stock is, by far, low-rise residential structures. Demand for these structures is growing: according to the UN anticipated growth in the world’s population from 2010 to 2050 is 1.4 billion with 97% occurring in the least developed regions, e.g., Africa and Asia. In Egypt, for example, it is estimated that at least 400,000 housing units are needed every year, and the current shortfall in available housing already exceeds 2,000,000 units. In Egypt if conventional reinforced concrete construction continues to be employed 50% of annual demand will not be met, leaving the situation to worsen (NRCHB 2010).

In addition to demands for more low-rise residential housing the demands for better low-rise residential housing must be recognized. These demands exist along two vectors: (1) sustainability: fully consider the important balancing act between economic, environmental, and social constraints when considering materials, means and methods, and long-term function of the structure, and (2) resiliency: increase the performance of low-rise structures against natural hazards, particularly earthquakes and hurricane/wind events. This confluence of greater demand in number and performance, for low-rise residential housing makes today an excellent time to question if traditional residential construction methods should be augmented by new systems.

To meet such a challenge, it is necessary to explore the latest construction technologies, and to create innovative building systems that have the potential to bring high-performance affordable housing within reach of new markets, particularly in developing regions. Beyond being affordable, these systems have to be flexible enough to suit local climate and site conditions, cultural and living habits, and spatial standards. Construction solutions also should reduce or eliminate the need for skilled personnel on the site, and ideally should be assembled with simple tools and errectable without machinery. Among the available construction systems that satisfy the previous conditions, light (cold-formed) steel framing systems (Figure 1) have proven to be a worthy alternative to traditional systems.

Potential advantages of such light steel framing systems include the high degree of dimensional exactness of the members, high strength-to-weight ratio of the members, high recycled content, and ease of construction. These qualities have lead cold-formed steel studs and tracks to be the framing method of choice for non-load bearing walls in mid- and high-rise construction worldwide. This proposal explores the use of cold-formed steel framing in residential housing with a focus on (a) developing new non-proprietary systems for light cold-formed steel framing with the potential to greatly improve building performance and flexibility, and (b) providing a series of building archetype studies that explore framing solutions in the U.S. and Egypt from economic, environmental, and sustainability metrics.

Figure 1: (a) Single family cold-formed steel framed house (www.steelframehousing.org), (b) Multi-family cold-formed steel framed building (photo credit: Don Allen (personal))
A.2 Summary of Previous Work

A considerable amount of research activity has been conducted to develop cold-formed steel (which is literally coils of sheet steel approximately 1 to 3 mm thick cold bent into shapes such as the C, Z, and hat) into a useful structural product. The pioneering work demonstrating the application of cold-formed steel to buildings and developing the first engineering design specifications was conducted at Cornell University by George Winter and his colleagues in the 1940’s and 1950’s. The research provided a means, for the first time, to handle the loss in strength and stiffness due to the use of members with such thin walls and how to handle the local buckling that inevitably results. A key finding of this research, and one that forms the backbone for efficiencies of these members, was that significant post-buckling strength existed and could be reliably incorporated in design. This research eventually lead to the American Iron and Steel Institute’s (AISI’s) specification for cold-formed steel, most recently embodied in AISI-S100-071. Fundamental aspects of the AISI Specification (AISI-S100) are found in cold-formed steel specifications worldwide.

In 2004 an entirely new design approach was added to AISI-S100: the Direct Strength Method. The Direct Strength Method integrates computational determination of the local cross-section stability into the design methods pioneered by George Winter. While previously design was limited to members that could be readily handled using classic plate stability, now an entirely new design space is opened up – essentially any member that can be roll-formed may have its strength reliability predicted by the Specification. The Direct Strength Method (Schafer 2008, AISI-S100-07 Section 1) was pioneered by the U.S. PI and shepherded through the Standards process by the PI. It is proposed herein to utilize this new tool to develop new classes and new systems of cold-formed steel members so that the technical performance of cold-formed steel structures may take a transformative advance.

In the early 1990’s AISI recognized that cold-formed steel framing (like that of Figure 1) had potential to be cost competitive with traditional low-rise structures and in cooperation with the U.S. National Association for Home Builders (e.g. see NAHB 1994, Waite 1994) developed the Residential Advisory Group. The work of this group eventually lead to the creation of a new group within AISI dedicated to developing framing standards: the AISI Committee on Framing Standards1 (AISI-COFS).

The AISI-COFS created and maintains a series of North American standards for cold-formed steel framing that attempt, when possible to treat the entire framing system, not just the individual members. AISI-COFS standards include: General Provisions (AISI S200-07), Product Data (AISI S201-07), Floor and Roof System Design (AISI S210-07), Wall Stud Design (AISI S211-07), Header Design (AISI S212-07), Lateral Design (AISI S213-07), and Truss Design (AISI S214-07). For example AISI S213-07 (Lateral Design) has had a significant impact on practice as this standard provides a means to determine the lateral strength of cold-formed steel systems used in wind and seismic demands. The standard provides compiled test results for cold-formed steel shear walls and diaphragms with a variety of sheathing, fastener spacing, stud spacing, etc. Specific seismic detailing provisions are also provided. These standards represent 20 years of industrial development in cold-formed steel framing and to date have only been applied in North America. This proposal provides a means to extend the application of these standards to design scenarios worldwide, particularly Egypt. The technology transfer of the

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1 The U.S. PI serves on this standards development committee
knowledge embodied in the AISI-COFS Standards is a powerful reason to perform the building archetype studies proposed herein.

In addition to engineering development issues related to construction management and cost have also been addressed. Direct cost comparisons between timber and light steel framing have been completed in isolated cases (Spelter 1979, Chini and Gupta 1995, 1997, Bateman 1997) including as recently as 2009 for a site in Utah (Perkins 2009). Recently, the interest in assessing sustainability of light steel framing has increased, while in the U.S. this has primarily focused on the LEED system and its system of “points”, life-cycle assessment methods utilized in Europe have lead to more in-depth work such as that by the U.K. based Steel Construction Institute (SCI P260, 307, 367 and 370) which cover construction costs, energy costs, and direct sustainability assessments. Taken in total the existing literature related to cost and sustainability provide a very incomplete picture of the current state of affairs leaving builders, particulary in new areas such as Egypt missing fundamental information necessary to pursue adoption.

A.3 Other ongoing projects that the project would complement
This project will complement NSF-CMMI #1041578: NEESR-CR: Enabling Performance-Based Seismic Design of Multi-Story Cold-Formed Steel Structures, PI: Schafer. In this existing grant tools are developed to extend efficient nonlinear time history modeling to cold-formed steel buildings, and experiments are conducted to quantify component, sub-system, and full building response. All of the investigated quantities are engineering performance metrics and all framing is conventional cold-formed steel framing with commodity shapes. In the project proposed herein a broader view of the cold-formed steel framed building is provided including building archetypes evaluated not only for engineering performance metrics, but for environmental and sustainability metrics. In addition, this proposal explicitly explores entirely new members and framing schemes thus this proposal broadens the scope of this existing award.

A.4 How US & Egyptian PIs came to work together in this proposal
The happy circumstance that lead to this proposal involves multiple connection points between the U.S. PI and his Egyptian counterparts. First, Dr. Maged Youssof of the Housing and Building Research Center in Giza Egypt (one of the Egyptian co-PIs) spent 1 year with the U.S. PI at Johns Hopkins University (2008-9 academic year). During that time they developed new research efforts in cold-formed steel design and extended existing efforts of Dr. Youssof on slender sections. Second, the U.S. PI's current graduate student, Mina Seif (Ph.D. expected October 2010), who will be a Postdoctoral Scholar on the U.S. team, was an advisee of the Egyptian PI (Dr. Abu-Hamd). Third, The U.S. PI serves as Vice-Chair of the Structural Stability Research Council and organizes the Annual Stability Conference – and this last year (2010) the Egyptian team attended the conference and presented their work, as did the U.S. PI’s research group, thus providing a venue for discussing emerging collaborative ideas. All of which lead to the proposal you find before you.

B Scientific and Technical Problems
A number of myths and problems represent barriers to progress in creating more affordable, resilient and sustainable housing with cold-formed steel. A common myth is that traditional framing systems have too much market momentum to ever be supplanted. While one cannot deny the power of past practice, it does not determine future decisions, particularly when current methods do not meet needs. Further, adoption of new materials may be slower in civil
engineering than other disciplines, but it is not zero – consider for example buried pipelines where: clay, iron, steel, reinforced concrete, prestressed concrete, HDPE, PVC, fiberglass, and others all readily compete for market share – from an engineering perspective it is illogical that low-rise buildings should be dominated by one traditional solution.

Another myth related to cold-formed steel framing is that it is not a “local” technology. Domestic timber industries and local concrete batch plants generally claim to be essentially local products (leaving this aside it is important to distinguish between hot-rolled and cold-formed steel). The importation of steel, where previously little steel construction had occurred, can be viewed by some with skepticism. Unlike hot-rolled steel where the final members (typically I-beams) are imported and shipping can be at great cost, only the coils of sheet steel are imported for cold-formed steel framing. The engineering technology is added locally by a roll-former, who creates the final members to be utilized. Though heavy equipment is required for roll-forming the scale is miniscule compared to a steel production facility. This arrangement allows for efficient scale-up of a domestic roll-forming industry\(^2\) supporting cold-formed steel framing.

Currently, cold-formed steel shapes are too simplistic. As a result maximum efficiency is not realized from these members and cold-formed steel structures remain more expensive than they need to be. Many manufacturers, focused on commodity production cannot yet envision the new design possibilities that have been opened up by advances in design methods and changes in design specifications. Current cold-formed steel framing mimics timber framing instead of maximizing its own possibilities. While mimicking timber may provide short-term comfort to the builder ultimately it means cold-formed steel construction suffers from many of the same inefficiencies as timber construction – particularly when it comes to accommodating any form of opening (window, door, etc). Further, key advantages of cold-formed steel construction such as the ability to readily vary the strength of members, even when the outside dimensions are constant are not taken advantage of to create optimal framing strategies.

The building industry is reluctant to change when costs are unknown. Basic questions need to be answered for adoption of new solutions to develop:

- what does cold-formed steel framing cost?
- how resilient is cold-formed steel framing?
- what is the sustainability of cold-formed steel framed homes?
- for all measures, how does cold-formed steel framing compare with traditional solutions?

Without this fundamental information the industry remains stuck in a suboptimal equilibrium – and continues to build and make only minor incremental improvements to the same solutions it has provided since the mid 20\(^{th}\) century or earlier.

A number of additional challenges remain that are out of the scope of this project. In particular, specific strategies for providing training and tooling/outfitting for builders interested in expanding into cold-formed steel framing is not addressed herein. A comprehensive market education study is also not addressed here, but ultimately would be necessary for any wholesale adoption. Finally, two important issues: thermal and acoustic performance of cold-formed steel framing is not specifically addressed here in terms of improved performance. Existing cold-formed steel framing solutions have shown that cold-formed steel framing can achieve excellent thermal and acoustic performance (CFSEI 2009) – but additional improvements are always needed in these areas – though they are outside the scope of the work proposed herein, beyond assessment of current technology for cost and sustainability metrics.

\(^2\) the most successful roll-forming companies are generally independent of the steel mills and buy their coil steel on the world market, U.S. examples include Dietrich and ClarkWestern.
C       Project Description and Detailed Plan of Work
To develop and explore the use of cold-formed steel in residential housing two major research activities are proposed:
• development of a novel non-proprietary cold-formed steel framing system, and
• building archetypes study.

The two studies are highly complementary, as the newly developed system will also be considered in the building archetypes study. The development of the new framing system will largely be the work of the U.S. team, and the building archetypes study of the Egyptian team.

C.1 Development of a novel non-proprietary cold-formed steel framing system
Cold-formed steel framing has not yet realized its potential. Currently, the framing systems employed (Figure 1) are largely direct translations of timber framing and the designs are component-based using only commodity sections (i.e. the lipped channel or “stud” and the unlipped channel or “track”). Over the last 10 years two new technologies have been developed and introduced into U.S. design specifications that allow for radical departure from this thinking: the Direct Strength Method (e.g. AISI-S100 Appendix 1) which allows for shape optimization in a far more robust way than previously possible, and Advanced (or second-order) Analysis Methods (AISI-S100 Appendix 2), which allows for frame optimization in a far more robust way than previously possible.

A non-proprietary framing system will be developed with these enabling technologies and include the full implementation of two key features – (1) the use of optimized shapes, and (2) the implementation of a ‘dual’ system whereby a primary cold-formed steel structural system and a secondary cold-formed steel structural system both exist blending the advantages of sparsely spaced primary frames conventionally used in hot-rolled steel construction with closely spaced stick framing methods conventionally used in timber construction. The key steps in the development of the novel non-proprietary framing system include:
1. Develop a library of optimal shapes for primary and secondary CFS members
2. Develop the new ‘dual’ system for walls and floors
3. Develop home archetype
4. Develop full framing solution for archetypical home
5. Demonstrate flexibility of ‘dual’ framing system
6. Develop price estimates etc. as needed for full archetype building studies

Each of the preceding steps are discussed and detailed below.

C.1.1 Develop a library of optimal shapes for primary and secondary CFS members
Cold-formed steel shapes in current direct translations of timber framing include the lipped channel (such as that of Figure 2a) that is employed for studs, joists, headers, jambs, etc. and the unlipped or plain channel that is employed as track. The shapes are designed essentially to mimic timber construction, at least in their common outer dimension, but are not optimal in any structural sense. Today’s cold-formed steel is largely the same as George Winter envisioned in the 1940’s.

Given the advancement in roll-forming technology, and the recent advancement in predictive methods formally adopted in design specifications the potential for a new generation of shapes exists. The potential payoff can readily be observed even in a simple ad hoc optimization as depicted in Figure 2, where options (b) and (c) provide a 270% and 370% (respectively) improvement in local buckling over a standard lipped channel stud. The example I section of Figure 2 (b) and (c) meets important constraints of current design: providing parallel
surfaces to attach sheathing and a flat web region that could easily have perforations for services, while at the same time the new section vastly improves the local buckling performance, and also the torsional performance as in the example section the shear center and centroid coincide and the principal axes are aligned with the geometric axes removing a complication with the use of singly symmetric sections such as channels.

Given the defined potential, formal optimization, both gradient-based and evolutionary/random-search techniques, will be utilized in the development of a family of new shapes for cold-formed steel framing. Unlike existing research in optimal design of cold-formed steel (e.g. Karim and Adeli 1999) this proposal will directly incorporate cross-section buckling analysis (using FSM Schafer and Adany 2006). By using numerical cross-section buckling analysis, instead of analytical design rules tied to specific cross-sections, the strength of any section can be provided and the optimal search can explore design spaces heretofore entirely ignored.

For example, the predicted strength of a column, \( P_n \), may be found by the Direct Strength Method (AISI-S100-07) as:

\[
P_n = \min\left[f_1(P_{cre}, P_y), f_2(P_{crd}, P_y), f_3(P_{crd}, P_y)\right]
\]

where \( P_n \) is the capacity, \( P_y \) is the squash load, \( f_1-f_3 \) are known nonlinear analytical functions, and then cross-section elastic buckling analysis is used to determine \( P_{crd} \) the distortional bucking load, and \( P_{cre} \) the global, or Euler, buckling load of the member. (The method exists for beams as well, though \( f_1-f_3 \) are different). Optimization requires maximizing \( P_n \) subject to constraints, which include basic constraints such as the width of the coil slit and thickness of the coil, but also constraints are drawn from the function: stud, joist, header, jamb, track (as is the loading).

Determination of \( P_{crf}, P_{crd}, P_{cre} \) can be non-trivial. Generally, in a problem with \( n \) DOF, the engineer/analyst is required to search the \( n \) DOF to manually identify the minimum \( P_{crf}, P_{crd}, \) and \( P_{cre} \). But here, recent work will be utilized that has provided a means to mechanically separate the deformations of the buckling modes in to those that are consistent with local, distortional, and global buckling through the use of constraint matrices, derived specifically to enforce the strain conditions relevant to a given mode (Adany and Schafer 2006a; Adany and Schafer 2006b; Adany and Schafer 2008). In this case the \( n \) DOF eigen-stability problem

\[
(K_e - \Lambda K_g)\Phi = 0
\]

where \( K_e \) is the member elastic stiffness matrix, \( K_g \) is the member geometric stiffness matrix, and the \( n \) eigenvalues/vectors are on the diagonal of \( \Lambda \) and columns of \( \Phi \), respectively; may be reduced, for example for local buckling, such that

\[
\left[R_e^T K_e R_e^T - \Lambda g R_e^T K_g R_e^T\right]\Phi_e \text{ or } \left[K_c^e - \Lambda K_g^e\right]\Phi_e
\]

where the work of Adany and Schafer defines \( R_e \) and \( \min \Lambda \) and therefore \( P_{crf} = \lambda_e P_{ref} \) may thus be determined directly. This allows the general eigen-stability problem to be re-cast as three
separate stability solutions, where the minimum $\lambda$ is of interest in each. The final objective function utilizes these minima and the functions, $f$.

C.1.2 Develop the new ‘dual’ system for walls and floors

As Figure 3(a) shows, conventional cold-formed steel framing is essentially mimickry of timber framing. This, in part, reflects a desire to use the dominant low-rise building process and was intended to allow for wide adoption by builders. Light framed construction (timber or current steel) may be understood as a dense network of slight members that is occasionally perforated to create openings for doors, windows, etc., and additional stiffening is required at the perforations. Heavy framed construction (reinforced concrete or hot-rolled steel) may be understood as a sparse network of heavy members that essentially utilizes a non-structural skin between the main structural members and thus has great flexibility with respect to interior layout and exterior openings. What is proposed here is the exploration of a hybrid, or ‘dual’ system where the entire structure is framed from cold-formed steel but the same members are not used throughout.

Figure 3 Framing for a low-rise cold-formed steel home (a) conventional in-line framing (SFA 2000), (b) new ‘dual’ frame cold-formed steel system mapped onto the wall framing detail of a, (c) ‘dual’ framing system with new (i) primary and (ii) secondary studs, (iii) combined load distribution and rim track, (iv) roof track, and (v) increased flexibility for penetrations

Consider Figure 3, in (b) a primary framing system is mapped onto the existing system (a) and in (c) an example of a ‘dual’ system is provided for the wall. The ‘dual’ system utilizes primary cold-formed steel members that are of greater stiffness and strength than secondary members (but that still share the same section depth so the wall line is not disrupted). The actual member shapes will be based on the optimization results of C1.1. Key features of the primary frame include semi-rigid connections between primary frame columns and beams, and beams that serve as track for the secondary frames as well as allow load redistribution around missing secondary frame members. The secondary frame is structural (i.e. it is not isolated from the primary frame) but the members will be lighter than conventional owing to the presence of the primary frame – greater flexibility in openings is an obvious advantage of such a system.
The relative stiffness difference between the primary and secondary system will be developed using 2nd order frame analysis and it is expected that a family of solutions will be initially identified. The connection details will utilize recent advances in cold-formed steel moment connections (Sato and Uang 2009, 2010, Uang et al. 2010) as well as detailed characterizations regarding semi-rigid connections in cold-formed steel beam-to-column connections developed for high capacity, high-rise, cold-formed steel storage racks (Filiatrault et al. 2007, Prabha et al. 2010, Gilbert and Rasmussen 2010).

Cold-formed steel has unique potential to utilize a ‘dual’ structural system. In timber, such a system is nearly impossible to realize because one cannot vary the strength and stiffness of individual members and still keep the outside dimensions constant, as a result members with varied properties (primary and secondary) cannot easily be used in the same wall-line. In concrete, the primary frame cannot be readily augmented with a secondary system without costly additional formwork and pours. A hybrid hot-rolled and cold-formed steel system can be imagined – but cold-formed steel production requires significantly less overhead and thus has greater potential for worldwide adoption.

C.1.3 Develop home archetype

The selection of the archetypical home to be explored with the new shapes and ‘dual’ framing system will be completed in conjunction with the building archetypes study: C2.1. A key feature of the archetypical home will be the fact that the even for the same footprint a large variety of different exterior and interior layouts is desired. It is worthy of mentioning that such a system would be capable of providing a traditional home, or a modern home (such as recently prototyped - Figure 4).

Figure 4 Prototype cold-formed steel home using sparsely spaced cold-formed steel moment frames (Newman 2010)

C.1.4 Develop full framing solution for archetypical home

A complete framing solution including member selection for the primary and secondary system, all detailing, both connections and sheathing, will be realized for the archetypical home.

C.1.5 Demonstrate flexibility of ‘dual’ framing system

Based on the archetypical home a series of alternative structures will be realized. The alternative structures will not be part of the building archetype study of C2, but rather will demonstrate the potential of the framing system.

C.1.6 Develop price estimates etc. as needed for full archetype building studies

Experts from industry will be utilized to develop realistic price points for the newly developed optimal shapes as well as the ‘dual’ system itself so that the building archetypes study will be realistic. As former President of the Cold-Formed Steel Engineers Institute and as a long-term member of the AISI Standards development committees for cold-formed steel, the U.S. PI has private contacts with (a) all the major U.S. manufactures including directors of product development at multiple cold-formed steel manufacturers, (b) numerous specialty engineers that design cold-formed steel structures, and (c) numerous builders in the U.S. that specialize in cold-formed steel construction. In addition, for Egyptian practice, the Egyptian PI has been an active
member of the Permanent Committee of the Egyptian Code of Practice for Steel Structures and Bridges since 1984 and is a registered Professional Engineer in Egypt since 1991. He has been working as a Consulting Engineer since 1980 and was involved in the structural steel design of many major projects in Egypt. These resources will be utilized to insure the price estimates employed in the building archetype study will be useful and realistic.

All of the work in items C.1 will be developed as a non-proprietary system. The goal is not to develop and market a particular solution; whether that be a new member cross-section or a new framing system. Industry has proven that it currently only has the ability to incrementally improve – this proposal envisions transformative advances – and has as a goal opening up new design possibilities for society as end-users, instead of new market niches for a few companies. In the 1940’s George Winter demonstrated that cold-formed steel could be a structural product and helped engineers design with this new material. This proposal shows how far one could go today with residential construction framed from cold-formed steel and aims to provide society with a new solution to one of its oldest problems.

C.2 Building Archetypes Study
Affordable housing does not imply low-performance. Indeed, for a structure to be sustainable it must be affordable, resilient, and provide the right compromise between environmental, economic, and social constraints. The objective of the building archetype study is to quantify the expected resiliency and sustainability of traditional framing solutions and alternative cold-formed steel framing solutions as measured in real places. The development of new residential housing solutions do not occur in a vacuum, beyond being affordable, any new system has to be flexible enough to suit local climate and site conditions, cultural and living habits, and spatial standards. Construction should reduce or eliminate the need for skilled personnel on the site, and it should be able to be assembled with simple tools and erectable without machinery. Further the materials employed and the structure created should be sustainable. All of these factors are considered and developed in the building archetype study, which has the following key steps:

1. Rural and urban site selection in the U.S. and Egypt
2. Architectural and Structural Design for Archetypes
3. Economic costs of site, structure, and construction
4. Environmental impact and sustainability measurement
5. Sensitivity studies.

Each of the preceding is detailed in the following.

C.2.1 Select Rural and Urban locations for archetype homes in U.S. and Egypt
Place is an important determinant of engineering and social demands. The building archetypes study will focus on an urban and a rural location in both the U.S. and Egypt. In addition, locations with significant earthquake and wind demands will be selected so that resiliency may be directly explored. Final locations and details will be selected in coordination with industrial partners.

C.2.2 Design by U.S and Egyptian Codes (AISI-COFS standards of high interest)
Architectural demands at each location will be established. Based on the location engineering demands will then be established. From these studies a framing plan will be developed at each site – the framing plan will consist of three alternatives:

• location appropriate conventional framing (U.S.: timber, Egypt: concrete),
• conventional/commodity cold-formed steel framing, and
• the new non-proprietary ‘dual’ cold-formed steel framing as developed in this grant.

Loading demand will follow standards that govern at the location (Egyptian Building Code, and ASCE 7). Design capacities will depend on the framing material. Traditional materials will follow governing standards (concrete in Egypt: Egyptian building code, timber in the U.S.: NDS). Conventional cold-formed steel will follow the AISI standards (AISI-S100-07, and the AISI-COFS family of standards discussed in Section A.2). The new ‘dual’ cold-formed system will follow the AISI standards, but augmented based on the findings of this research. In addition to framing the structural system the non-structural system will also be detailed – thus for each archetype building a complete set of architectural and structural drawings and engineering calculations will be provided.

C.2.3 Determine (initial) economic costs, of structure + construction

For each building archetype the economic costs for site, structure, and construction will be estimated. For conventional framing (concrete in Egypt, timber in the U.S.) this is a relatively straightforward proposition. For the cold-formed steel alternatives construction estimates include greater uncertainty (site and materials costs can be estimated with similar rigor as the traditional solutions). A series of scenarios will be established so that construction costs (and sustainability metrics) can be fully understood/bracketed.

C.2.4 Measure environmental impact and sustainability measures

Sustainability assessment requires the direct introduction of value judgments in performance assessment. Engineering performance against hazards, generally only makes such value judgments indirectly – for instance by setting probabilities of failure (safety factors). The balance point between economic, environmental, and social constraints varies for different cultures and even places within a culture. Thus, it is anticipated that use of North American centric sustainability measurements such as LEED (USGBC 2009) and Green Globes (2010) based on BREEAM (2010) while necessary will not be completely sufficient. Complete life cycle assessment approaches such as BEES developed by the U.S. National Institute of Standards and Technology (NIST 2008) hold the promise of objectivity, but ultimately monetizing every factor requires data and assumptions that are simply not completely available.

The Egyptian Housing and Building Research Center (two of the co-PIs are from this Center) has recently worked on developing Egyptian codes for energy efficient residential and commercial buildings\(^3\). This experience combined with existing sustainability metrics will be utilized to develop a sustainability scoring system that will be used to compare the building archetype studies. The system will utilize existing standards (primarily LEED) but categories and points will be modified to more directly reflect the importance of ‘place’.

C.2.5 Perform Sensitivity studies

It is recognized that even with a significantly detailed study that final assessments are sensitive to the assumptions made. To address this situation a series of sensitivity studies are planned. These studies will encompass the following variations:

• architectural demands: energy and space demands/configuration,
• material costs: volatility in material costs can be high and will be included,

\(^3\) ASCE 6th International Engineering and Construction Conference (IECC’6): Advances in Affordable Housing and Green Construction, Cairo, Egypt, 28-30 June 2010.
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- construction costs: labor costs and assumptions on builder expertise/efficiency,
- sustainability metrics: large variety of sometimes qualitative inputs to be explored.

While the initial analysis includes the expected conditions, best/worst case scenarios in a 10 year timeframe will be considered in the sensitivity study. The goal of the sensitivity studies will be to bracket the sensitivity of the final answers in a manner useful for decision-makers.

C.3 Detailed Plan of Work

A two year project is planned for completing the proposed work. The research activities of both the U.S. and Egyptian team are detailed in Figure 5. Vertical arrows in Figure 5 indicate important exchanges between research the development of the novel non-proprietary cold-formed steel framing system (activity 1) and the building archetypes study (activity 2).

C.4 Project Team

The project team is summarized in Table 1 and complete CVs are provided in the proposal package. For the U.S. and Egyptian PI’s brief narratives, as follows, are also provided.

Table 1 U.S. and Egyptian Project Team

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<td>Prof. Benjamin W. Schafer</td>
<td><strong>P.I.:</strong> Prof Metwally Abu-Hamd</td>
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<tr>
<td>Swirnow Family Faculty Scholar</td>
<td>Professor of Steel Structures</td>
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<td>Professor and Chair</td>
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<td>1- Dr. Mina Seif</td>
<td><strong>Members:</strong></td>
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<tr>
<td>Postdoctoral Scholar</td>
<td>1- Prof Mohammed R. Badr</td>
<td></td>
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<tr>
<td>Department of Civil Engineering</td>
<td>Head of Structural and Metallic Construction Inst.</td>
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<tr>
<td>Johns Hopkins University, USA</td>
<td>National Research Center of Housing and Building, Giza, Egypt.</td>
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<td>2- Dr Maged H. Youssof</td>
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Figure 5 Detailed Work Plan and Gantt Chart
Benjamin W. Schafer is the Swirnow Family Faculty Scholar, Professor, and Chair of the Department of Civil Engineering at Johns Hopkins University in Baltimore, MD. He received his B.S.E. with Honors and Distinction from the University of Iowa in 1993, and his M.S. and Ph.D. in Structural Engineering from Cornell University in 1995 and 1997 respectively. He worked as a practicing engineering from 1998-2000 and has been on the faculty at Johns Hopkins since 2000. He has authored 32 journal papers (of 43 total) and numerous conference papers specifically related to cold-formed steel structures. He serves on the committees that author the U.S. cold-formed steel specifications (AISI-COS and AISI-COFS). He serves as Vice-Chair of the Structural Stability Research Council (SSRC), and is a Past-President of the Cold-Formed Steel Engineers Institute, as well as Former Chair of both the SSRC Task Group on Thin-walled Construction and the ASCE-SEI Committee on Cold-Formed Steel. He regularly consults on product development issues related to cold-formed steel.

Metwally Abu-Hamd is a Professor of Steel Structures and Bridges in the Structural Engineering Dept of the Faculty of Engineering at Cairo University, Egypt. He received his B.Sc. form Cairo University, Egypt in 1971 and his M.Sc. and Ph.D. in 1975 and 1977 from Duke University, USA. On the Academic level, Dr Abu-Hamd served as the Structural Engineering Department Head from 2007 to 2009 and served as Director of the Cairo University Civil Engineering Research and Studies Center from 1994 to 2005. He authored two text books on the design of Plate Girder Bridges and Steel Bridges. Recently he established a Virtual Education Lab in the Faculty of Engineering at Cairo University. Dr Abu-Hamd research interests include optimization of steel structures, composite columns, load distribution in bridges, and local stability of plate girders. Dr Abu-Hamd has published numerous research papers and supervised several M.S. and Ph.D. theses in the field of Structural Steel Design. He received the Cairo University Award for Distinguished Research in Structural Engineering in 1985 and the Egyptian Government State Prize for Engineering Sciences in 1989. Dr Abu-Hamd is a member of the Egyptian Universities Committee for Promotion of University Professors since 2001. On the professional level, Dr Abu-Hamd is a member of the Permanent Committee of the Egyptian Code of Practice for Steel Structures and Bridges since 1984 and a registered Professional Engineer since 1991. He has been working as a Consulting Engineer since 1980 and was involved in the structural steel design of many major projects in Egypt.

C.5 Private sector and technology transfer
This grant provides fundamental advances for low-rise structural framing systems through the development of new cold-formed steel profiles and new cold-formed steel framing systems. The developed profiles and framing systems will be non-proprietary and are intended to unequivocally demonstrate the formidable new design spaces that have been opened up by recent advances in member and system design for cold-formed steel systems. The new profiles and systems will specifically be shared with U.S. and Egyptian industry, including manufacturing, engineers, and builders.

Adoption of new low-rise building solutions also requires that developers, planners, and owners (in addition to manufacturing, engineering, and builders) fully understand the advantages, disadvantages of employing new technology. This grant specifically provides the information necessary for these decision-makers: cost, environmental impact, and long-term
sustainability assessments are critical information. In addition, Egyptian builders have agreed to build a demonstration model of the designed archetypes.

Finally, the U.S. is a world leader in the development and use of cold-formed steel framing. Egypt provides an entry point for markets in Africa and the Middle East, not to mention its own market, which is stable – Egypt’s economy grew by 5.3% in 2009/2010\(^4\). The research and industrial connections resulting from this grant are a powerful benefit for the private sector.

**D Expected Outcomes**

This research will develop and quantify the potential for cold-formed steel framing to provide resilient and sustainable residential housing. It is expected that cold-formed steel framing will be shown, on a performance-basis, to be more desirable than traditional housing solutions in a broad variety of design situations given certain conditions, conditions that will be specifically detailed in the course of the grant, are met. As a result it is expected that in the U.S. cold-formed steel framing will grow as a percentage of new construction, and in Egypt (including the Middle East and Africa) cold-formed steel framing will become an established business using modern engineering to provide a resilient and sustainable solution to the housing needs of the region.

An entire family of new cold-formed steel shapes, appropriate for use in cold-formed steel framing, but significantly more advanced than conventional channel sections, will be developed. It is expected, and indeed supported by the outreach efforts of this grant, that major U.S. and Egyptian manufacturers will explore these new shapes for potential commercialization. An entirely new low-rise steel framing system will be developed. The new ‘dual’ framing system will demonstrate how to design a highly resilient cold-formed steel framed home without sacrificing design flexibility. This grant provides specialty engineers who design from cold-formed steel examples for both member and system design that push current technology to its limit and thus enable them to further innovate what is possible in cold-formed steel structures.

A complete framework for how to gauge which low-rise building solutions are the most desirable from both an economic and sustainability viewpoint will be developed. Through the building archetype studies the embodied knowledge of U.S. cold-formed steel specifications (which are the world’s most advanced in this area) will be transferred to Egyptian engineers and researchers for adoption in Egyptian codes. In addition to evaluating existing technology (timber, concrete, and conventional cold-formed steel) the grant provides a means to evaluate entirely new framing solutions (e.g., the new ‘dual’ framing system for cold-formed steel), thus providing a means for the marketplace to explore a large variety of framing options. An understanding of exactly what factors are most critical in determining cost and sustainability will be established.

**E Prior Support from NSF**

PI Schafer’s CAREER award, CMMI-0448707 (5/2005 – 6/2010, $400,000); titled: CAREER: Structural Stability and Thin-walled Structures investigated (i) development of a novel decomposition technique of use in model reduction and modal identification in computational structural stability problems, and (ii) the practical extension and verification (including experiments) of computational structural stability into design of thin-walled steel members. This grant resulted in the production of 11 journal articles (7 published, 3 In Press, and 1 Submitted), 3 Technical Notes for practicing engineers, 1 book chapter, 18 refereed conference papers and 3

\(^4\) Economist Oct 9th-15th, see [www.investment.gov.eg](http://www.investment.gov.eg) for further details
non-refereed conference papers. The grant provided training for 2 Ph.D. students, 5 undergraduate researchers, and 4 high school researchers. The grant also resulted in the construction of a new testing facility for thin-walled members under multiple DOF actions.

In addition the PI has recently been awarded two new grants: CMMI #1041578: NEESR-CR: Enabling Performance-Based Seismic Design of Multi-Story Cold-Formed Steel Structures, 09/01/2010, $923,752 and CMMI #1000167: Collaborative Research: Reconfiguring Steel Structures: Energy Dissipation and Buckling Mitigation Through the Use of Steel Foams, 07/01/2010, $128,890. Both of these recent awards are initiating their research efforts.

**Conclusions**

Affordable, sustainable, resilient shelter is a basic societal need. Cold-formed steel framing, even in its current limited form, has proven itself as a viable alternative to traditional construction methods. In some markets, such as the framing for non-load bearing walls in mid and high-rise buildings, cold-formed steel has essentially supplanted traditional methods due to its high performance, including strength, stiffness, and dimensional accuracy as well as high recycled content, combined with low costs and ease of construction. In the residential market cold-formed steel framing currently plays a minor role in the U.S. and essentially no role in Egypt or in important developing markets including Africa and the Middle East.

This proposal envisions significant improvements in both members and framing systems comprised of cold-formed steel. Leveraging advances in analysis and design an entirely new family of optimal cold-formed steel member shapes will be developed. These new shapes will be utilized in a novel ‘dual’ framing system that combines the best of traditional heavy framing (hot-rolled steel and concrete) with that of light framing (repetitive in-line framing such as in timber) to create a highly resilient primary system, capable of incorporating significant design flexibility, but still allowing the secondary members to contribute structurally to the performance.

Adoption of cold-formed steel framing, including the newly developed members and ‘dual’ system will be placed on a rational performance-basis. Full structural plans, engineering performance specifications, site, material and construction costs, environmental impact, and sustainability metrics will be developed for archetype homes in Egypt and the U.S.. The archetypes will allow direct comparison of traditional, conventional cold-formed steel, and the newly proposed cold-formed steel systems. Sensitivity studies will provide a means to quantify the role of uncertainty and the robustness of the conclusions from these studies. Model homes will be constructed in Egypt. Taken together the project represents a collection of transformative ideas and analysis that will allow decision-makers (owners, engineers, builders, planners, etc.) to fully understand the potential for cold-formed steel in residential housing.

**Intellectual Merit:** The research proposed herein advances significantly the application of cold-formed steel framing to residential housing. This is achieved through development of an entirely new cold-formed steel framing structural system, and through careful building archetype studies that specifically weigh the balance between engineering performance and sustainability metrics. In total the study will provide a template for how to evaluate new framing systems in residential housing with a worldwide view, and specifically demonstrate this approach for cold-formed steel framing. The U.S. PI (Schafer) is the driving force behind significant changes in U.S. design specifications that enable new highly efficient cold-formed steel shapes to readily be designed and is uniquely positioned to explore and provide novel solutions for cold-formed steel framing.
The Egyptian PI (Abu-Hamd) has a long experience in the performance of steel structures and construction management of steel structures. They are joined by senior personnel: Hanna in Egypt and Seif in the U.S., who have spent significant time in both research groups. A detailed implementation plan is provided for the research. The resources required largely utilize the already active work at both institutions.

**Broader Impacts:** The sociological broader impact is largely focused on the creation of a new U.S.-Egyptian partnership on cold-formed steel structures. Personnel exchanges to deepen the experience are budgeted and planned for. Although Egyptian ethnicity is not particularly well defined by standard designations used in the U.S., they constitute an underrepresented group worthy of growth and outreach. The PI has a strong record of dissemination to academic and industry – both channels will be utilized in this research. Specifically, outreach to industry will include U.S. codes and standards organizations (AISI-COFS) as well as annual meetings of builders and practitioners (Metalcon). Cooperation with building contractors shall also include financing the building of demonstration models of the developed designs in Egypt. The larger goal of the research is to create residential housing that meets engineering performance and sustainability targets with much greater efficiency than current solutions. The partnership with Egypt insures that the full breadth of the problem is explored and that new solutions will have maximum global benefit.