Structural Design and Materials - Research Needed to Reinvent Housing in the United States

Steven M. Cramer[1]

Abstract

Structural design and materials are the cornerstones of house designs in the United States. The current model of house design is approximately 50 years old and has not adjusted to the change in demands associated with evolving resource demands and other world changes. Focus Group 2 on Structural Design and Materials prepared eight position papers covering recent advances in housing research in the areas of innovative and sustainable materials, fire protection, durability issues, performance based engineering and design for high wind and other extreme loads. Through a series of presentations and roundtable discussions, the group identified research to address four urgent need areas: home safety and security, affordability and constructability of housing, sustainability and durability in housing construction, and functional house design. Specific example research topics were identified in each need area.

Keywords: housing, structural design, materials, safety, sustainability

Introduction

Fundamental to housing are the materials and configuration of the materials used. For many Americans, as early in life as the first reading of the common "Three Little Pigs" children's nursery rhyme, the safety and quality of the home is equated with the materials and configuration of materials used in the construction. As you may recall, the little pig with a house of one type of material was unsafe and eaten by the big bad wolf while the little pig with a house of a different material and design remained safe and happy. With good reason, our perception of the effectiveness of our housing at a very personal level is tied to the materials used and their configurations.

The ways materials are organized, shaped and connected are characterized in the engineering world as the structural design. Materials are shaped into components with different functions – some tied to the physical safety and integrity of the building, and others tied to operational and aesthetic functions. Historically, the structural design for housing has been a series of prescriptive rules that have evolved from a blend of structural engineering consideration of the basic laws of physics (gravity) and guidelines developed from craftsmanship.

Focus Group #2 of the NSF Housing Research Agenda Workshop examined research needs in structural design and materials for housing. The panelists in Focus Group #2 were all respected faculty listed in Table 1. The focus group deliberations included a presentation from each

[1] Professor, Dept. of Civil and Environmental Engineering, 1415 Engineering Drive, University of Wisconsin-Madison, Madison, WI 53706

panelist which outlined their particular contributions to housing research and responses to a series of broad questions concerning housing research. These questions included:

1. Are current housing structural systems technically failing? Where and in what ways (design, material, performance, construction, code enforcement)? With which societal impacts (affordability, diffusion, market acceptance, regulations, environment, occupant health, etc.)?
2. What are the facts that support the need for research in structural design and materials in housing?
3. Is a "revolution" or an "evolution" needed in housing structural systems? Why? What are the indicators? What are the constraints?
4. How does (or should) structural design and materials interface with the other focus areas?

Following the individual presentations, the group engaged in a series of structured round table discussions that identified urgent needs and opportunities to technically redesign and reinvent housing. This paper presents the collective thoughts and opportunities identified by this working group in the areas of new materials, improved utilization of existing materials, and new rational structural design advances.

Table 1. NSF Housing Research Agenda Workshop – Structural Design and Materials Participants

Name	Affiliation
Steven M. Cramer (Focus Group Leader)	Dept. of Civil & Environmental Engineering University of Wisconsin-Madison
William G. Davids	Dept. of Civil & Environmental Engineering University of Maine
David W. Dinehart	Dept. of Civil Engineering Villanova University
Daniel Dolan	Dept. of Civil and Environmental Engineering Washington State University
Lawrence T. Drzal	Dept. of Materials Science & Mechanics Composite Materials and Structures Center Michigan State University
Robert N. Emerson	School of Civil & Environmental Engineering Oklahoma State University
Mervyn J. Kowalsky	Department of Civil Engineering North Carolina State University
Kimberly E. Kurtis	School of Civil and Environmental Engineering Georgia Institute of Technology

The development of materials and structural design for housing in the United States is a story of innovation (Lienhard 2003). Prior to about 1830, housing was an adaptation of European architecture, but in contrast to Europe, the United States had an abundance of timber and a shortage of specialized skilled craftsman. The US quickly developed timber housing that required a less skilled labor force. Mortise and tenon joints (requiring skilled craftsmanship) were soon replaced by nails prompted by automated nail-making, a US innovation. In 1832, the balloon frame design, consisting of parallel lumber framing members spaced on a regular interval (16 in or 24 in) and extending the full height of the building, was invented and dramatically cut the cost of housing and other wood building construction. Wood materials, and this general framework of smaller dimension structural members interconnected with a sheathing and nailed connections, have dominated in U.S. housing ever since. Despite its construction efficiency, balloon frame design possessed two major shortcomings. First, fire could spread very quickly up the open vertical shafts between framing members and sheathing. Secondly, the long framing members were more costly than shorter members.

Platform framing was introduced in the 1920's and like balloon framing is another variation of light-frame construction involving parallel structural members in walls and roofs connected by sheathing. Platform framing involves building each floor, stack by stack without the framing members continuing through multiple stories (balloon framing). After roughly 100 years of dominance, the balloon frame gave way to platform framing in the 1930's and 1940's. With the shift to platform framing, board sheathing was replaced with structural wood panels. The first plywood was displayed in 1905, but it did not see widespread application as a building component until the 1940's. Similarly, gypsum plaster systems were replaced by gypsum board panels. These innovations generally improved the structural integrity of houses with the exception that platform framing without special attention to floor interconnection details did not provide a complete load path for lateral and uplift loads.

The current system of light frame wood members covered with structural sheathing has been the predominant material and structural system in housing for at least the past 50 years. Advances to this system have tended to be small and incremental. New developments including the use of structural insulated panels to replace wall or roof sheathing systems, light gauge steel framing members, and concrete wall systems with insulated stay-in-place concrete forms represent only small portions of housing construction. Engineered wood products have entered the market place but are generally utilized with the same construction and structural design methods that have been in place for 50 years. The engineered structural design of housing has never been explicit and instead has evolved more from practice and experience than purposeful design calculation. A history of satisfactory structural performance has developed over the past 50 years, but this observation is derived primarily from houses that have tended to be relatively simple structures with not more than two roof ridge lines at 90 degrees to each other, rectangular floor plans with highly partitioned interiors and sizes in the range 1200 to 2500 sq. ft. of floor space.

Houses of current construction tend to have more complicated gable roof systems, open and adaptable floor plans and a much larger range of sizes. In just the past 15 years, the average single family home has grown from under 2000 sq ft to over 2300 sq ft and the number of homes of 1200 sq ft or less has shrunk to an all time low of 5% of all single family home construction (NAHB 2003c). The number of new houses constructed each year with four or more bedrooms has increased by over 50%. Structural design and materials have not advanced with the changing consumer preference toward larger and more complex houses. Recent housing losses in hurricanes, earthquakes and fires have revealed weaknesses in current design and construction.

Structural design and the materials used in housing have historically developed into single purpose systems. Different layers of materials and structural components are brought individually to the jobsite and assembled with each typically satisfying a single primary function.

For example, a stud wall consists of studs to provide structural resistance to gravity loads combined with exterior sheathing to provide resistance to lateral loads and then insulation is placed in the wall to provide energy efficiency. Gypsum wallboard will then be placed on the inside surface of the wall to provide a finished surface or in some cases a layer of fire protection. Four separate components are thus providing four separate functions. The focus group agreed that structural design and materials in housing can be dramatically improved through the development and application of structural designs and materials that capitalize on multifunctional components. The need to rethink the 50-plus year old structural design of housing and to harness emerging materials has never been greater.

Future Research Directions

Researching new design methods and new materials is not simply a matter of better structural design and better materials. Research in structural design and materials is fundamental to the nature of home construction and performance in the following urgent need areas:

- home safety and security,
- affordability and constructability of housing,
- sustainability and durability in housing construction, and
- functional house design.

The greatest opportunities for the most significant advances in housing with structural design and materials are not discrete or sequential advances in any one issue identified above, but instead will be those investigations and developments that simultaneously address multiple issues. The focus group identified and developed the research directions described below.

Structural Design and Materials: Safe and Secure Homes

As described earlier, structural design and materials have always been the cornerstones of home safety and security, and basic laws of physics dictate that the fundamental supporting structure will continue to play a primary role in building safety. Conventional construction does not automatically provide safety for all situations and rational engineering design cannot be taken for granted as an unnecessary step. Today and tomorrow, the challenges to home safety and security are and will come from a combination of new threats and old.

<u>Terror and Domestic Crime:</u> Providing a structure that is secure from break-in and attack whether the source is domestic crime or terrorism is intrinsic to the structural design and materials used in housing. Structural design and materials as part of the building envelope play a primary role in resisting physical attacks to the building structure regardless of cause. Materials used in the building envelope and interior when properly designed can also play a role in mitigating or detecting biological, chemical or radiological hazards. The research challenge will be to develop structural frameworks and materials that are economical, aesthetically pleasing to consumers and at the same time offer new levels of safety.

<u>Health & Home Environment:</u> Mold and air quality are health safety issues that have captured national attention. As indicated by Congressman John Conyers, Jr. in introducing the H.R. 5040:

The United States Toxic Mold Safety and Protection Act: "Exposure to mold growth in residential, public and commercial buildings is believed to have caused serious medical conditions which include bleeding lungs, digestive problems, hair loss, nausea, loss of memory, reduced cognitive skills, and death. Property damage from mold growth has destroyed millions of dollars in real estate and forced homeowners to the curb. We cannot eliminate mold. However, there are steps that can be taken to minimize the dangers of indoor mold growth." New materials combined with specific attention to the design of the building envelope hold the potential to largely eliminate the mold problem and to address a variety of indoor health threats.

Fire: The fire hazard in housing results in approximately 3000 deaths and $6B property loss each year and disproportionately impacts lower socio-economic segments in the U.S. The United States has historically had one of the highest fire death rates in the industrialized world (FEMA 1997). In 2002, over 75% of all structure fires occurred in residential construction and the $6B property loss in one and two family dwellings was an 8% increase from 2001 (Karter 2003). The number of fire fighters lost annually in residential structure collapses has tripled since the 1980's (NIST 2003). The fire threat has taken on a new dimension as posed by the wild land-urban interface fires we have witnessed during the past 5 years. The California wildfires in 2003 caused approximately $2B in property losses alone.

The level of fire safety is not explicitly defined and incorporated in house design. Fire safety could be dramatically improved by developing engineering design principles and new fire resistant and nontoxic materials for residential buildings (Cramer and White 2004).

Natural Hazards: Hurricanes, tornados and earthquakes continue to cause significant losses of life and property in housing. The Northridge Earthquake caused over $20 billion of damage to wood frame construction in southern California (Emerson 2004). Hurricane Andrew's damage exceeded $30 billion to south Florida. Single and multifamily wood home construction in the United States has historically developed to resist gravity loads (snow and occupancy loads) and performed reasonably well when subjected to lateral loads (wind and seismic) due to the high structural redundancy inherent in balloon and platform construction (Dolan et al. 2004). However, as the building architectural features have changed, the concept of providing lateral load resistance in houses has been oversimplified and the requirement of a functional load path too often neglected. The result has been tremendous property losses in high wind and seismic events.

The past twenty years has seen extensive use and application of innovative systems and materials for seismic hazard mitigation but use of these technologies has concentrated almost exclusively on their use in steel, concrete and masonry commercial structures (Dinehart 2004). With the exception of a few cases these advanced systems have yet to be exploited in wood frame residential construction. The primary lateral load resisting system in housing is the shear wall. Many researchers have observed that shear wall capacity is limited by the capacity of the sheathing-to-framing connections and thus one of the more effective ways to improve the structural integrity of housing subject to severe lateral loads is with improved sheathing systems (Davids et al. 2004).

The definition of performance levels that are rationally based on life safety risk and property loss risk are desperately needed (Dolan et al. 2004). When combined with development of new design procedures, pre-engineered products and construction practices that effectively implement the design, the losses to natural hazards promise to be significantly reduced.

Structural Design and Materials: Affordable and More Constructible Housing

The past 20 years has been one of the largest growth periods in U.S. construction of housing. Monthly housing starts hit a 19-year high in November 2003 (NAHB 2003a) Annual housing starts in 2002 showed a 60% increase from 1982 (NAHB 2003b). This growth has been driven by a period of relative affordability despite skyrocketing land values in some locations. Interest rates at 45 year lows and low to moderate costs in construction materials have enabled housing to remain affordable for many income levels, but this situation is unlikely to continue. Housing affordability for lower income individuals and families has been and continues to be a major challenge.

Interest rates are predicted to increase and the costs of construction materials are increasing dramatically. The price of hot-rolled coil steel in the US increased by 66% in a 10 month period in 2003/2004 (Hagenbaugh 2004) and the price of oriented strand board, the most common structural sheathing used in house construction, increased 250% in 2003 (Derus 2003). The OSB price increase alone can increase the price of a house by $3000 to $10,000. Affordability of housing is typically measured by several different definitions of an affordability index. The affordability indices for housing are typically a function of mean household income and the median-priced home in a region, and these indices are generally increasing. Conversely, global pressures have restricted the rise of US incomes at the same time that increasing global demands are driving up costs of raw materials and building products. These trends that are now developing will have an increasingly negative impact on the affordability of housing.

Affordability and constructability are explicitly linked with the structural design and the materials used. Building materials and labor to construct the structural design are the largest cost components in house construction. The structural design will define the materials used in the superstructure and the structural configuration will largely dictate the labor tactics used to complete the construction. History vividly shows the importance of structural design and materials on affordability and constructability through the advent of balloon construction in the 1800's.

One promising approach to the affordability problem is the development of building envelopes and structural systems consisting of new materials and building products that incorporate multiple functions. Sheathing products or components that combine the functions of structural resistance, thermal insulation, and fire resistance into one product have the potential to provide significant cost savings. Combined-use or multifunction components offer the potential for cost saving as the individual cost of separate single use components will be reduced or eliminated. Considerable research is needed to first make such innovations possible and then to demonstrate economy.

Greater affordability can be achieved through increased factory-based prefabrication of subcomponent assemblies where greater structural performance can be designed into the component (Emerson 2004). Prefabrication can also provide new ways of resisting lateral load in addition to improving affordability (Davids et al. 2004). Pre-fabricated elements can incorporate better performing construction details and elements, and remain economical due to the efficiency of their automated factory assembly. New materials that require more sophisticated or proprietary installation methods can be accommodated. Higher quality control inherent in pre-fabricated elements may result in the more efficient use of advanced engineered materials. Potential affordability impacts exist in developing byproduct and waste materials into lower cost structural components and insulation (Drzal et al 2004).

Structural Design and Materials: Sustainable and Durable Housing

Demolition debris occupies 40% of land fill space (US EPA 1999). Research has confirmed the perception that newer house construction is less durable than historical house construction, accelerating the cycle of demolition and reconstruction. One recent study has shown houses only 2 years old show signs of five or more years of aging (Orlando Sentinel 2003). Consumers are increasingly seeking and demanding "certified green" building products that meet a variety of environmental and sustainable resource qualification criteria. It is clear that a fundamental change in housing construction that decreases the waste flow of materials from irreplaceable resources and utilizes sustainable resources is needed. The development of new biobased materials from renewable sources is one strategy for improving the sustainability of house construction practices (Drzal et al 2004, Mohr et al. 2004). New combinations of biomaterials with conventional construction materials offer the opportunity to both improve durability and at the same time utilize renewable resources. Combinations of wood fiber with a portland cement based matrix materials are emerging as accepted house siding products and with research and development are poised for growth into other building products and components (Mohr et al. 2004). Materials with triggered biodegradability would improve the current unsustainable nature of housing construction. Durable materials which are designed with intrinsic sensors which allow them to detect deterioration and ultimately to maintain themselves; self-healing housing materials are believed by the focus group to be technologically possible.

Structural Design and Materials: Functional Homes

Both structural design and materials dictate the type and nature of functional working spaces of houses. Consumers have shown a growing preference for open interiors as opposed to the highly partitioned interiors prevalent 20 or more years ago. The structural design and specifically the lateral resistance have not kept pace with these preferences and do not provide the structural integrity that coincides with consumer's current interior preferences (Dolan et al 2004). New structural design methodology that replaces the current prescriptive design methodology would allow house structural designs to adapt with consumer preferences. Open and flexible interior spaces with a structural outer shell would be a logical outcome in a performance driven structural design environment. However, considerable research is needed to establish a rational performance based design environment for houses, and substantial additional effort will be required to ensure wide implementation of such a design environment.

Structural Design and Materials Research Topic Summary

The broad areas of impact for structural design and materials research in housing include: home safety and security, affordability and constructability of housing, sustainability and durability in housing construction, and functional house design. There are many specific ideas and research efforts in structural design that will impact these urgent need areas and there was no attempt by the focus group to restrict creativity through a limited list of topics to address the urgent need areas. As examples of significant areas of research to address the urgent needs identified above, the following specific research ideas are presented as examples.

To address safety and security:

?? Identification and quantification of performance levels that ensure safety and minimize property damage for range of hazards including fire, high winds, and earthquakes.
?? Development of rational performance based design criteria and specifications for houses that reduce the reliance on prescriptive conventional construction.
?? Expanding the knowledge base and design procedures to offer novel and improved uses for existing construction materials to improve safety from hazards and overall durability.
?? Development of mold-resistant and nontoxic building materials.

To address affordability and constructability:

?? Development of pre-engineered and prefabricated building components that possess improved structural performance, intuitive installation that does not require skilled labor and that can be demonstrated to lower the cost of housing.
?? Development of multifunction sheathing components that, for example, combine structural performance with thermal and sound insulating qualities, and address mold and other air quality issues.

To address sustainability and durability:
Development of biobased materials and multifunction components that exhibit improved durability, economy and recyclable characteristics.

?? Development of materials with intrinsic sensing capabilities, allowing for detection of conditions which may lead to material deterioration or hazards to occupants.

To address functional house design:

?? Development of performance based design procedures to replace one-type fits all conventional prescriptive construction.
?? Development of innovative structural systems and building envelopes that allow for reconfiguration and changing use of interior spaces while maintaining structural integrity.
?? Holistic analysis of housing construction, including materials, components, and methods, to understand interactions between each and their functionality as a system; this analysis ultimately will lead to optimization of the "housing system" for performance.

Crosscutting Impact of Research

The focus group believed that advances in structural design and materials have tremendous potential for revolutionizing the way houses are designed and function. The most significant future research efforts will cut across not only the focus groups of the research workshop but will involve other disciplines. More importantly, most of the significant problems and opportunities are not cleanly defined along traditional disciplinary lines. There is considerable overlap with the problems to be researched by engineers aligned by discipline with this focus group and those aligned with the other focus groups. Table 2 illustrates some of the anticipated linkages.

Table 2. Crosscutting Impact of Broader Research Topics

#	Research Topic	Focus Area Overlaps[1]					Other Fields
		1	2	3	4	5	
1	Home Safety and Security			X		X	Health sciences for airborne hazards
2	Affordability and Constructability	X		X			Industrial engineering
3	Sustainability and Durability			X		X	Chemical engineering, chemistry, botany, plant sciences
4	Functional House Design	X		X	X	X	Architecture, Electrical engineering

[1] Focus Areas: 1. Construction Management and Production, 2. Structural Design and Materials, 3. Building Enclosures, Energy and Indoor Air Quality, 4. Housing Technology, Community and The Economy, 5. Systems Interactions and "Whole House" Approach

Justification of Research in Structural Design and Materials of Housing

Proposed academic research in most forums is judged by its intellectual creativity and the potential impact on society. Different approaches to the areas of research identified in the workshop may or may not possess intellectual merit and creativity and thus must be judged individually. Successful research proposals in the theme areas (home safety and security, affordability and constructability of housing, sustainability and durability in housing construction, and functional house design) would be expected to possess at least one or more of the following merits:

?? Exhibit a fundamental science-based approach to the integration of materials with design, construction, maintenance, and operation.
?? Provide a significantly improved understanding of functionality and performance of building systems.
?? Provide a verifiable definition and quantification of building performance expectations that go beyond life safety.
?? Provide new multifunctional components through the use of new technologies, materials science, fundamental mechanics or a combination of all three.
?? Provide an engineered design for recyclability of materials, components and larger assemblies.

The benefits to society for research in home safety and security, affordability and constructability of housing, sustainability and durability in housing construction, and functional house design are implied by the thematic names. The research emanating from these theme areas would be expected to quantitatively show reduced risk to life and property loss. Technology would be developed that improves sustainability and durability of components. Affordability and improved constructability are expected outcomes.

Summary

Safety and security in housing is largely undefined and provided at undefined levels by outdated prescriptive building requirements. The property losses resulting from fire, weather, and seismic events are large. After 20 years of growth, the home building industry and the home buying public face new challenges. Rising material costs and higher interest rates will pressure the industry to find and implement new efficiencies. Consumer preferences have changed to favor more flexible and open buildings constructed from building products that are as environmentally benign as possible. These challenges can be met with an investment in research in the structural design and materials used in home building.

As examples of significant areas of research to address the themes identified above, the following specific research ideas are presented as examples.

To address safety and security:

?? Identification and quantification of performance levels that ensure safety and minimize property damage for range of hazards including fire, high winds, and earthquakes.

?? Development of rational performance based design criteria and specifications for houses that reduce the reliance on prescriptive conventional construction.

?? Expanding the knowledge base and design procedures to offer novel and improved uses for existing construction materials to improve safety from hazards and overall durability.

?? Development of mold-resistant and nontoxic building materials.

To address affordability and constructability:

?? Development of pre-engineered and prefabricated building components that possess improved structural performance, intuitive installation that does not require skilled labor and that can be demonstrated to lower the cost of housing.

?? Development of multifunction sheathing components that, for example, combine structural performance with thermal and sound insulating qualities, and address mold and other air quality issues.

To address sustainability and durability:

?? Development of biobased materials and multifunction components that exhibit improved durability, economy and recyclable characteristics.

?? Development of materials with intrinsic sensing capabilities, allowing for detection of conditions which may lead to material deterioration or hazards to occupants.

To address functional house design:

?? Development of performance based design procedures to replace one-type fits all conventional prescriptive construction.

?? Development of innovative structural systems and building envelopes that allow for reconfiguration and changing use of interior spaces while maintaining structural integrity.

?? Holistic analysis of housing construction, including materials, components, and methods, to understand interactions between each and their functionality as a system; this analysis ultimately will lead to optimization of the "housing system" for performance.

References

Cramer, S.M. and White, R.H. (2004) Fire resistant design in housing – status and opportunities. *Proceedings of the NSF Housing Research Agenda Workshop*, Feb 12-14, 2004, Orlando, Florida. Eds. Syal, M., Hastak, M., and Mullens, M. Vol 2, pp. Focus Group-2, Paper-2.

Davids, W.G., Dagher, H.J., Cassidy, E.D., Martin, K. and Gardner, D. (2004) FRP-reinforced oriented strand board panels in wood-framed shear wall construction. *Proceedings of the NSF Housing Research Agenda Workshop*, Feb 12-14, 2004, Orlando, Florida. Eds. Syal, M., Hastak, M., and Mullens, M. Vol 2, Focus Group 2, 162-171.

Derus, M. (2003) Builders, buyers caught in wooden vise. *Milwaukee Journal Sentinel* Oct. 5, 2003 Edition.

Dinehart, D.W. (2004) Supplemental damping in woodframe structures. *Proceedings of the NSF Housing Research Agenda Workshop*, Feb 12-14, 2004, Orlando, Florida. Eds. Syal, M., Hastak, M., and Mullens, M. Vol 2, Focus Group 2, 102-111.

Dolan, J.D., Ohanehi, D., and Dillard, D. (2004) Use of innovative connectors and new combinations of materials to address weaknesses in light-frame construction. *Proceedings of the NSF Housing Research Agenda Workshop*, Feb 12-14, 2004, Orlando, Florida. Eds. Syal, M., Hastak, M., and Mullens, M. Vol 2, Focus Group 2, 94-101.

Drzal, L.T., Mohanty, D.K., Burgueno, R. and Misra, M. (2004) Biobased structural composite materials for housing and infrastructure applications: opportunities and challenges. *Proceedings of the NSF Housing Research Agenda Workshop*, Feb 12-14, 2004, Orlando, Florida. Eds. Syal, M., Hastak, M., and Mullens, M. Vol 2, Focus Group 2, 129-140.

Emerson, R. (2004) Moment resistant connections in prefabricated wood frame construction. *Proceedings of the NSF Housing Research Agenda Workshop*, Feb 12-14, 2004, Orlando, Florida. Eds. Syal, M., Hastak, M., and Mullens, M. Vol 2, Focus Group 2, 153-161.

FEMA (1997) Fire death rate trends – an international perspective, Tri- Data Corporation for the Federal Emergency Management Agency and the United States Fire Administration.

Hagenbaugh, B. (2004) Steel prices soar 66% in a world market 'gone mad'. *USA Today*, <http://www.usatoday.com/money/industries/manufacturing/2004-02-20-steel_x.htm> (April 1, 2004)

Karter, M.J. Jr. (2003). 2002 U.S. fire loss, *NFPA J.*, Sept./Oct. 2003.

Kowalsky, M.J. and Wight, G.D. (2004) Application of traditional materials in non-traditional ways for improved housing construction, *Proceedings of the NSF Housing Research Agenda Workshop*, Feb 12-14, 2004, Orlando, Florida. Eds. Syal, M., Hastak, M., and Mullens, M. Vol 2, Focus Group 2, 141-152.

Lienhard, J.H. (2000) Engines of our ingenuity: an engineer looks at technology and culture. Oxford ; New York : Oxford University Press.

Mohr, B.J., El-Ashkar, N.H., and Kurtis, K.E. (2004) Fiber-cement composites for housing construction: state-of-the-art review. *Proceedings of the NSF Housing Research Agenda Workshop*, Feb 12-14, 2004, Orlando, Florida. Eds. Syal, M., Hastak, M., and Mullens, M. Vol 2, Focus Group 2, 112-128.

NAHB (2003a) Housing starts hit a 19-year high in November. National Association of Home Builders. <http://www.nahb.org/news_details.aspx?newsID=679> (March 30, 2004)

NAHB (2003b) Annual housing starts. National Association of Home Builders. <http://www.nahb.org/generic.aspx?sectionID=130&genericContentID=554> (March 30, 2004)

NAHB (2003c) Characteristics of new single-family homes (1987-2002). National Association of Home Builders. <http://www.nahb.org/generic.aspx?sectionID=130&genericContentID=374> (March 30, 2004)

NIST (2003), Newsletter, Fall 2003, <http://www.fire.gov/newsletter/fall2003/page_four.htm> (January 6, 2004)

Orlando Sentinel (2003) Building homes: building problems. Orlando Sentinel series of articles, <http://www.orlandosentinel.com/news/local/orl-buildingproblems-stories.htmlstory?sm=23>. (April 1, 2004)

U.S. EPA. (1999) Characterization of building-related construction and demolition debris in the United States, EPA document 530-R-98-010. <http://www.epa.gov/epaoswer/hazwaste/sqg/c&d-rpt.pdf> (March 30, 2004)