Design!

Jim Fisher's keynote talk at this year's NASCC: The Steel Conference offered tips on how to be a better design professional. Here's what Jim had to say.

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HOW CAN WE, AS ENGINEERS, BEST ACHIEVE SUCCESSFUL DESIGNS IN STRUCTURAL STEEL? Design, as defined in the *Dictionary of Architecture and Construction*, is: "To compose a plan for a building." Our job as design engineers is to produce construction documents, plans, and specs. Many engineers wrongly emphasize analysis and calculations. They are but a means to the goal: a design.

Design is neither solely calculations nor construction documents; rather, it is a synthesis of techniques used to communicate a concept that constructors bring to reality. The AISC manual is titled the *Steel Construction Manual*, not the "Manual of Steel Design." The AISC specification is titled the *Specification for Structural Steel Buildings*, not the "Specification for the Design of Steel Buildings."

Engineering design is not purely science. As we know, engineering is also an art. It is the art of design that is difficult to quantify and model.

Jim Wooten, an engineer and part-time philosopher with AFCO Steel in Little Rock, Ark. once said, "The way we design is similar to how we weigh pigs in Arkansas." His analogy can be paraphrased this way: In Arkansas, they attach two baskets to either end of a pole and then carefully balance the pole over a log fence. They place the pig in one basket and fill the other basket with rocks until perfect balance is achieved. Then they guess the weight of the rocks.

Perhaps Wooten was illustrating the "art" part of design. Design should not involve guessing, although at times we must use educated guesses.

What is a successful design?

The answer varies, depending to whom the question is asked. For example:

To the owner of a building, a good design is one in which the building meets its intended function; one that does not leak, one with no cracks in the floor slab, and one with construction costs that came in under budget.

To the young designer, a good design is usually thought of as the building of least weight that will carry intended loads; in other words, it is one that is well-engineered.

To the senior project engineer, a good design is a building that satisfies the owner, and one for which the construction documents caused little or no confusion during and after construction.

To the owner of the firm, a good design is one with which the client is pleased, thus paying promptly, and one from which his or her firm makes a profit on the project.

As a designer of structural steel buildings, you are a part of a team: The team of engineers, fabricators, detailers, erectors, and material suppliers. A successful design is the one from which the team members and the owner are all satisfied. This generally occurs when all team members make a profit on the project, and the building owner believes he or she paid a fair price for the structure.

A successful design can only be accomplished with quality construction documents and cooperation among the team members. Design is not a success until construction is complete and the structure functions properly.

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Achieving Successful Designs

Engineers must ask the right questions regarding stiffness, strength, stability, and constructability to achieve a successful design. There is no checklist of rules or questions that one can apply and answer in order to declare that his or her design is perfect, safe, and successful.

Design and construction go together like partners in a three-legged race. Both are individuals, but they only win the race by acting in coordination. As I mentioned before, as a designer of structural steel buildings, you are a part of a team. This team has contractual relationships with one another, and it is the team that can help each member the most. This requires mutual respect that is often lacking in our adversarial world.

The contractual environment in which we design in the U.S., i.e. design then bid, often puts a barrier between the designers and the contractors. Design-build projects eliminate most of these barriers. However, designers and contractors, even in the design-bid environment, must work together in order to achieve a successful design.

I believe the following comments and lessons will assist in achieving successful designs.

What are you going to do when first given a design project?

This question was first posed to me by my company commander when I was a second lieutenant in the U.S. Army Corps of Engineers. My response was that I would gather my squad leaders, discuss the project (mission), and then give assignments. The captain said, "Wrong. The first thing you do is go to the mess hall, get a cup of coffee, and think about the assignment. It is not until you have thoroughly thought through the project that you begin to work on the design."

It is difficult for me to follow this advice because, as my colleagues know, I am a classic "A" type and want to get moving on things. When I do not follow this advice, my design, at some point, generally "runs amuck."

The success of any design depends upon communication. Always remember design concepts are communicated through structural plans and details.

Think about the big picture.

A second lesson I learned relatively early in my design carrier is to think about the big picture. The big picture for a successful design is to understand your client's needs and, as mentioned earlier, to understand the needs of the other team members.

As a young, and what I thought to be "hot shot," engineer, I went to the engineering design office of a major steel producer to inform them as to how, with my design of their steel mills, they would save thousands of dollars on each project. At that time, this particular company was performing all of its mill building designs in house. I informed the vice president of engineering that if he would change their design concept, which made use of cantilever columns, and instead design and install horizontal bracing at the bottom chord of the roof trusses, many dollars would be saved in column steel and foundations because the large lateral loads from the overhead cranes would be more efficiently distributed throughout the structure.

After explaining the concept, the vice president of engineering said okay and asked, "How long will it take you to design the horizontal bracing for each crane runway aisle?"

I replied about one week to determine the sizes and to design the connections (incidentally, today it would take longer because I would use the computer).

"How long will it take your draftsman to draw up the design?"

I replied about two weeks.

"How long do you think it will take the detailer to do his job?"

I replied, "I don't really know, but probably a couple of weeks."

"How long do you think it will take the fabricator to fabricate all of the horizontal bracing?"

Again I replied, "I don't really know, but I am sure a few weeks."

"And how long do you think it will take the erector to install this bracing (which is roughly 80' up in the air)?"

Don't know, but I am sure it will be several weeks.

The VP replied, after adding up the time, "So, it will take approximately nine weeks to get the bracing installed. Jim, we have a $3.5 million budget for this mill. Your cost-saving horizontal truss system will cost us approximately $6 million in interest, plus several million dollars in delaying the start-up time for the mill, and this does not include the cost of the bracing detailing, materials, fabrication, or erection. Will the truss system save that much in steel and concrete?"

Needless to say, the horizontal truss system was not used in the design.

The big picture means you must listen to and think about your client's needs.

Think constructability from the very beginning.

Constructability is defined by the Construction Industry Institute as "the optimum use of construction knowledge and experience in planning, design, procurement, and field operations to achieve overall project objectives." What this really means to me is, "Can the structure be built safely with relative ease and speed?"

The list of constructability considerations is extensive, but here are a few of the major items to be considered:

- Minimize the number of anchor rods per column.
- Provide permanent bracing that can be used as temporary bracing.
- Make sure that all beams can be brought into place without interference or having to spread columns apart.
- Provide adjustability in your design. Consider mill and fabrication tolerances by using shims and oversize or slotted holes where required.
- Check that tolerances do not accumulate, causing fit-up problems.
- Check to see that the tolerances specified match your expectations of the final product.
- Make sure that there is adequate access for welding and bolting.
- Check that beams do not have to be severely coped, i.e. deep members framing into shallow members.
- Eliminate overhead welding.
- Have realistic specifications that match your actual intent and design requirements.
- Use materials that are readily available.
- Minimize the amount of loose material for details.
- Provide straightforward connections that can be erected without added temporary provisions.
- Check for camber differences on adjacent members.
- Make sure members have sufficient width for elements bearing on them.
- Run cantilever beams over column tops whenever possible for safety in erection.
- Have steel deck span all in the same direction.
- Don't use moment base columns bearing on concrete piers.
- Avoid moment connections into the weak axis of columns.
- Indicate AESS judiciously. Just because structural steel can be seen in the final design, doesn't mean that it must be fabricated and erected using the stricter standards associated with AESS.

How can you best help the team?

As the engineer, you can help make a design successful by your actions. Understanding the needs of the detailer, fabricator, and erector is not complicated and can be summarized as follows.

Fabricator/Detailer: The fabricator wants you to provide a design that will permit the material to flow continuously through the shop. This means that your design should not require welding to a column or beam if the design also requires the drilling or punching of holes in the same member. Drill and punch lines are different lines than the welding lines. It costs money to transfer a column or beam from one line to another. The material will not flow through the shop if such transfer must be made. Fabricators and detailers suggest the following to achieve a successful design:

- Use standard AISC connections: single plate shear connections and single angle connections.
- Use field bolted moment connections.
- Keep the design simple.
- Provide understandable plans.
- Minimize changes.
- Release mill orders and detailing only when complete. And if not complete, inform the architect, contractor, and fabricator of the areas that are not yet complete.
- Repeat member sizes whenever possible (least weight is not least cost).
- Show all reactions on the drawings: axial, shear, moment, and transfer forces.
- Answer the detailer's questions promptly; in other words, REALLY FAST.
- Approve shop drawings in a timely manner.
- Remember: steel fabrication is a business.

Erector:

- Minimize the amount of loose material for field installation.
- Use maximum practical column lengths (two- or three-story with splices 4' above the floor).
- When possible, provide permanent bracing in the design that can also be used as temporary bracing.
- Keep the design simple and provide readily understandable plans.
- Remember: steel erection is a business.

Notice the commonality of needs for each of the team members. Listen to the fabricator, the detailer, and the erector. They have gained practical knowledge in their day-to-day experiences of putting many projects together. This knowledge can be instrumental in achieving a good design.

Design Steps

The following steps, in approximate order, will lead to a successful design:

- Determine serviceability criteria for beams and spandrel members.
- Determine the lateral drift criteria.
- Determine fire protection criteria.
- Determine any insurance requirements, such as Factory Mutual requirements.
- Determine the direction of roof drainage (primarily for single-story structures).
- Determine the structural system; i.e. braced frames, moment frames, shear walls.
- Determine the loads on the structure.
- Determine the type of connections to use for the lateral load system.
- Determine which members will be used for the lateral load system.
- Determine member sizes based on the drift criteria and the other serviceability criteria.
- Perform analysis to check conformance with drift criteria.
- Check member sizes for strength.
- Select member sizes that make the connections work.
- Design connections.
- Draw plans and details to an appropriate scale.
- Check to make sure that the design has been correctly transferred into the construction documents.
- Use judgment.

The Role of Judgment

Good judgment is the single most important factor in providing success and reliability in engineering design.

I am concerned, that in recent years, we are eliminating room for judgment in analysis and design.

The definition of judgment, according to Webster's, is "the capacity to assess situations or circumstances shrewdly and to draw sound conclusions."

From Henry Petroski's book, *Design Paradigms*: "Improvements in analytical tools and models cannot alone improve the practice of engineering and the reliability of its products, for the choice of the input to and the interpretation of the output from analysis involve extra scientific judgment. Indeed, efforts to improve engineering design by concentrating on the refinement of its more easily quantifiable analytical models and tools may actually be counterproductive if those efforts come at the expense of studies aimed at improving the assumptive and interpretive skills of engineers."

We must use engineering judgment in our analysis and designs. Furthermore, we must supplement the results of our analysis and design with thoughtful and careful considerations of the results.

Many of the solutions to the constructability issues cited earlier are in fact judgment calls that we make to provide successful designs. We also make judgments routinely until they become second nature. For example:

- We neglect forces or moments that are of minor consequence.
- We assume pinned connections when in actuality they are not pure pins.
- We neglect moments in four-bolt anchor rod bases.
- We assume steel is isotropic and homogeneous.
- We neglect secondary moments in truss chords and web members.
- We neglect small differential settlements.
- We do not calculate principle stresses.
- We neglect stresses from rolling, bending, cutting, and welding of steel members.

A few comments on judgment:

- Judgment minimizes human errors.
- Judgment is what gets a design headed in the right direction.
- Judgment must be applied as the design progresses in order to prevent the design from going astray.
- Judgment is required to separate major details from minor details.
- Judgment guides us on what to include in our analytical models.
- Judgment guides us as to what portions of the design should be independently checked.
- Judgment guides the designer on what to check at the construction site.
- Judgment catches errors.

How do we obtain judgment?

- Judgment comes from experience.
- Judgment comes from examining the poor judgment or mistakes of others and of oneself.
- Successful engineers of the past are our best teachers of judgment. What engineers were doing in past times has relevance to what we should be doing today.
- Talk to contractors, subcontractors, and material suppliers about your designs.
- Use AISC resources.
- Toss around ideas with your colleagues.
- Go to seminars on design.

Sound judgment is our most important engineering tool. Let your judgment guide and temper all your design decisions.

The Role of the Computer

Some of the best comments regarding the use of computers in design have come from Jim Wooten in his 1972 *Modern Steel Construction* article entitled, "Wooten's Third Law and Steel Column Design."

He explains in the article that, "Wooten's First and Second Laws are concerned with sex and, although they are much more interesting, are not germane to this discussion." But the Third Law is this: "The acquisition of uncommon knowledge inhibits the application of common sense."

Later in the article, he continues: "Perhaps the best illustration of the Third Law is the computer, a machine that can absorb millions of bits of the most sophisticated, uncommon knowledge and still remain abysmally stupid, becoming completely unhinged if one jot or tittle is misplaced in its program. Unfortunately, like the computer, we tend to become programmed rather than educated.

"The computer renders obsolete the necessity of rationalizing and simplifying problems—or even of understanding them. No one need feel guilty of using simple solutions when the computer can make them extremely complicated.

"It has never been clear to how many places an inaccurate answer must be carried to make it accurate."

Successful and practical designs can only be obtained through the interaction of the designer and machine. This is a one-on-one situation. The designer, not the computer, must be free to make all pertinent decisions to solve a particular problem. In my opinion, it is important to examine the results of the analysis before selecting and designing the members in the structure. By examining the analysis results, judgments can be made as to the behavior of the structure and how to refine your preliminary design. The computer is a tool that should be used to assist your work as a designer. Analysis results that differ from your judgment and common sense should be carefully scrutinized.

Obtaining Successful Designs by Reducing Design Errors

All engineers and forensic specialists agree that *human error* is the major cause of design failures. Thinking in terms of preventing failure is a major way that successful designs are accomplished. Visualizing the limit states for each element, each connection, and for the structure as a whole allows one to determine if safety is accomplished in the design. One of the features of the 2005 AISC specification is that for each strength calculation addressed, all of the known limit states are cited.

Understanding past design errors increases our judgment, and thus is beneficial for reducing *human error* in today's designs.

According to Lev Zetlin (1988), "Engineers should be slightly paranoiac during the design stage. They should consider and imagine that the impossible could happen. They should not be complacent and secure in the mere realization that if all the requirements of the design handbooks and manuals have been satisfied, the structure will be safe and sound."

I'd rather be in an over-braced and under-designed building, than in an over-designed, under-braced building.

Design changes, especially those made late in the design process, can introduce new failure modes or bring into play hidden failure modes. Any design change, no matter how small, must be analyzed with the objectives of the original design in mind. Be very careful about making design changes during the course of a design team meeting or construction meeting. How often have you agreed to a change, only to realize when you are driving back to the office that the change negatively affects another part of the design?

Be particularly aware of designs that are of larger scale or size than you have performed in the past. A principle of design that is all too often forgotten is the effect of size or scale.

Checking calculations for logic and mathematical errors is extremely important. Checking plans and specifications for inconsistencies and omissions can save expensive field correction costs and can catch failures when they are still on paper. It is important to remember that the original designer can continue to overlook the same errors he or she made, whereas a peer or colleague may discover latent errors and mistaken logic. Peer review on all designs is very beneficial, but the reviewer should be brought on board at the conceptual design phase of the project.

R. Hauser (1979), from his paper "Lessons from European Failures," concluded that "the most efficient way to improve structural safety or to reduce the overall effort to maintain a certain level of structural safety is to refine the methods of data checking (to catch design errors) and not to refine the models of analysis."

A Few Design Quips to Guide You

- **Create Flintstones designs.** *Mike West, Computerized Structural Design*. These are designs that Fred and Barney can design and build. Creating a Flintstones design is a corollary to the old adage, KISS—Keep It Simple, Stupid. Remember that some poor soul is going to erect your design in the blazing heat of the day or in the freezing cold. Complexity is the last thing the worker needs to worry about.
- **Be a ksi.** *C.K. Wang, University of Wisconsin*. Professor Wang would often say in the classroom to imagine yourself as a ksi on a journey from one part of the structure down to the earth. You must be able to find your way through every member, every connection, every weld, every bolt, and every screw without being overstressed. We now call this "load path."
- **The trickle theory.** *Me*. The trickle theory is the opposite of tracking loads through the structure. The trickle theory presumes that the ksi will go somewhere and find its way to earth without engineering analysis. Don't practice the trickle theory.
- **If it works, don't mess with it.** *Anonymous*. There is great wisdom and judgment in this statement. A proven design will work any multitude of times so long as the scale of the structure does not change.
- **You cannot do just *one* stupid thing in the design**. *Mike West, Computerized Structural Design*. Once you use bad judgment in a design, more bad decisions will have to be made.
- **Learn from your failures**. *Anonymous*. The best way to obtain judgment.
- **Less is more**. *Mies van der Rohe, Illinois Institute of Technology*. Similar to KISS, only more eloquent.
- **God is in the details**. *Mies van der Rohe, Illinois Institute of Technology*. The details are the design.
- **If it looks good, it probably is good.** *Dick Schleis, Computerized Structural Design*. A part of judgment. Proportions

often indicate if a structure or structural components are designed correctly. Get to the job site. Designs look different when you see them in real life.

- **Don't worship the weight god.** *Anonymous*. Least weight is rarely least cost.
- **If we can prevent local and lateral buckling, then we should be able to design any structure based on stiffness and serviceability considerations.** *Jim Wooten, AFCO Steel*. Structural steel is a wonderful material. If we prevent buckling in any form, a steel structure will find a way to stay up.
- **I'd rather be in an over-braced and under-designed building, than in an over-designed, under-braced building.** *Me*.
- **If you can't rough it out on an envelope, you shouldn't design it.** *Bill LeMessurier, LeMessurier Consultants*. Again judgment. You should know the answer to the problem before you start with sophisticated analytical analysis.
- **Don't hide under your desk.** *Mike West, Computerized Structural Design*. You cannot solve a problem relative to your design if you don't face it head on. React, and react quickly.
- **Strive for structural simplicity.** *Fazlur Khan*.
- **Don't get lost in your own technology.** *Fazlur Khan*.

Assisting Future Engineers in Achieving Successful Designs

We all learn from our predecessors. We as engineers, fabricators, detailers, erectors, and educators can best assist future engineers in becoming successful designers.

Engineers

- Be a mentor. Take time to relay your years of experience to younger, less experienced engineers.
- Talk about judgment to your young engineers, and talk about the importance of judgment in the design process.
- Be open to design suggestions by fabricators, erectors, and detailers.
- Embrace the future. Design is not a static process. Methods change. You will obtain successful designs by embracing the future, but study carefully new ideas before embracing them.
- Give of your time to AISC, ACI, ASCE, and other professional organizations. You will learn the latest technology to "pass on." You can also make a contribution to the profession, and in addition you will obtain satisfaction and lasting friends.
- Look beyond what we do in the United States. You can gain insight to interesting design concepts from what happens overseas.

Fabricators, Erectors, and Detailers

- Give time to AISC, especially to technical committees: the academics and engineering practitioners need your input.
- Take time to talk to young engineers about design issues and provide input as to how certain procedures affect project costs.
- Provide input through various AISC publications and seminars to engineers and educators as to how certain design features affect fabrication costs.
- Fabricators: offer tours of your facilities to designers.
- Sponsor a least one talk at NASCC on what the engineer should know about detailing, fabrication, and erection. Engineers need more guidance from erectors and detailers. These presentations can never be given too many times.

Educators

- Teach students to think creatively. I know that severe limits exist in classroom time, but more open-ended problems are invaluable to the student's education.
- Concentrate on fundamentals. It is the job of the employer to teach how to design.
- Stress the importance of logical analysis, having the correct boundary conditions, and having the mathematics correct. Using the correct theory to solve a problem does not in itself make the structure safe.
- Give students as many exercises as possible to develop judgment, and that ask questions like, "Does the answer look correct?"
- Teach plastic steel design. Plastic design procedures provide the student with fundamental knowledge on how structures behave and help the student develop judgment.

Younger engineers should:

- Learn to communicate. Engineering is a people business.
- Get involved with professional activities.
- Don't forget that "God is in the details."
- Get out to the job site. You will learn a great deal.
- Think about how the "IN" basket on your desk gets filled. You will not have employment unless projects are sold. Projects are sold by doing correct and complete work in a timely manner. Help your firm make a profit. Profit is not a dirty word, and without it the firm will not exist.

To achieve successful designs, remember to:

- Think about the big picture
- Think constructability
- Be a team player, and
- Use your judgment at all times.

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