

## **Role of Tolerances and Process Capability Data In Product and Process Design Integration**

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### **Abstract**

A case from the authors' experience reveals that dimensional tolerance, in terms of physical dimensions of components and their position within the system; interact to compound the process variability and uncertainty within a project. Variability adds to the costs of a process with long cycle times, high work in progress levels; wasted capacity due to low utilization of resources; lost throughput, and a general increase in waste (poor quality and increased scrap) (Hopp and Spearman 2000). Early constructability research supports this observation: as it identified dimensional tolerances as a major factor in ease of construction and subsequently cost and schedule (O'Connor 1989 and CII 1986). Though constructability research has developed many tools for application to design, none appear to have focused on how to identify appropriate tolerances. In addition, other industries outside AEC have made significant improvements by carefully measuring and understanding the effects of tolerances within their systems. Quantifying dimensional tolerances for construction operations and materials, and developing strategies to mitigate their effects is therefore an important objective in research and design practice. Based on a case study, a strategy is recommended in which product designers are challenged to design systems that accommodate most process variability without compromising project goals.

### **Introduction**

Construction in some ways resembles mass production within the car industry where defective cars sat at the end of the assembly line, waiting to be fixed by a team of skilled technicians. This practice creates additional rework to fix problems buried by follow-on activities and requires special skills and knowledge. Womack and Jones (1996) describe these repairmen as a new specialty craft in the car industry. Today in AEC, construction proceeds largely ignoring when a process is out of tolerance, because the tolerance is too tight to achieve or not specified. When a problem results the efforts, knowledge and skills of the entire project team are employed to devise a fix. Crews specialize in fixing, develop new skills and become another necessary but scarce resource in an industry already plagued with a shortage of skilled labor. It is not always possible to fix the problem when it occurs. With specialization and separation between trades, often an individual worker will not understand the effects subtleties in

their work have on follow-on activities. The problem may even be systemic to the overall process design itself. In most manufacturing industries many of these problems have been overcome. Data obtained by measuring process variation of all types including tolerances facilitate integrated product and process design, replacing over-the-wall engineering (Gerth 1997).

In the 1800's, the need for interchangeable parts created the need for tolerance representation. Tolerance standards and techniques have been evolving ever since. Analytical techniques well documented since the 1950's, statistical techniques since the 1970's, and computer based systems since the 70's are developed to evaluate the effects of individual component tolerances on the assembly, function, and quality of a product. ASME Y14.5 and 10 ISO standards are the current dimensioning and tolerancing standards (Voelcker, 1997). Tolerances are defined as "the range of variation permitted in a specified dimension or location without impacting structural integrity, operating capability, or abutting components" (CII 1993). Tolerance analysis takes a given set of component tolerances and calculates on the resultant the variation in the assembly. Through iteration, component tolerances are tightened to meet assembly tolerances. Tolerance allocation uses overall assembly tolerances and allocates component tolerances based on relative contributions to the assembly and production costs. Tolerance allocation can result in looser component tolerances and better matching of product and process (Trabelsi et al. 2000, Gerth 1997). Yet, work is still required to make these systems more efficient for complex assemblies, standardized for 3D assembly analysis, and fully generative for functional equations (Gerth 1997, Schultheiss and Hinze 2000). Statistical tolerance tools studied in response to excessive manufacturing costs associated with worst-case tolerance analyses rely on detailed process capability data (Gerth 1997). Process capability refers to the inherent variability in the parameters or properties of a processes output including specified dimension or location. Design for manufacturing (DFM) and design for assembly (DFA) were introduced in the 1980s to denote the use of process capability and cost data to influence product development processes. Several manufactures have claimed a 50% reduction in production costs (Ulrich and Eppinger 2000).

Tolerances are also a factor in product quality. Quality tools such as statistical process control (SPC), introduced by Shewhart in 1931 and later expanded by Demming, Juran, and Ohno, look for ways to understand and improve process capabilities (Pyzdek 1999). Methodologies to implement SPC such as Taguchi, Six-Sigma, and ISO 9000 are widely used across manufacturing industries. With these tools problems are identified avoiding design iteration, costly prototyping, production design iteration, high production costs, production delays, and low product yields (Gerth 1997). AEC is behind other industries in this regard. Process capability data in addition to tools for understanding how tolerances impact the function and other parameters of the product or project are required. An example of contrast between construction and mechanical manufacturing is a case study on construction of high performance equipment foundations. While the manufacturer had detailed understanding of the "tolerance allowance" for the facility it was apparent the foundation designer was inexperienced in considering the relationship between construction operations and foundations (Septelka and Cooper 2000).

Though construction practitioners occasionally use process capabilities in terms of productivity and quality to inform process improvement, there is little to no evidence of their analysis of dimensional tolerances. On going review of the literature and interviews with practitioners revealed an example where pavement quality measures on thickness was gathered

and used to inform either product or process design (Schmitt et al. 2000). Structural engineers in California may argue that the variability in plumb-ness of an erected structure and the resulting redistribution of loads is negligible compared to the dynamic loading conditions considered for seismic design. Although from a structural integrity dimensional tolerances appear negligible, they may affect operating capability or abutting components. The following case study illustrates some impacts of tolerances and how process data may be used upstream to mitigate them.

### Example Case: Tunnel Roof-to-Wall Connection

This case looks at the connection between the soldier-pile tremie-concrete slurry wall and the composite steel-and-concrete roof system for a cut-and-cover tunnel construction. Figures 1 and 2 illustrate the connection as designed. The design consists of an erection bracket/seat (arrow 'a' in Figure 1) welded to the W36 X 300 soldier pile, a small clip angle (b) welded to the top of the plate roof girder and the face of the pile mostly for stability during erection, and a 1.9 cm ( $\frac{3}{4}$ " bent plate double web cleat (c) which forms the main structural connection. The 18.3 m (60') to 27.4 m (90') roof girders are spanned by stay-in-place (SIP) steel formwork with a reinforced concrete slab on top. Shear studs (not shown) welded to the top of the roof girder transfer loads between the girder and the slab. The roof girders are subjected to the vertical loads of the fill on top of the roof plus the surface traffic, and to the horizontal loads to resist earth pressure on the walls.

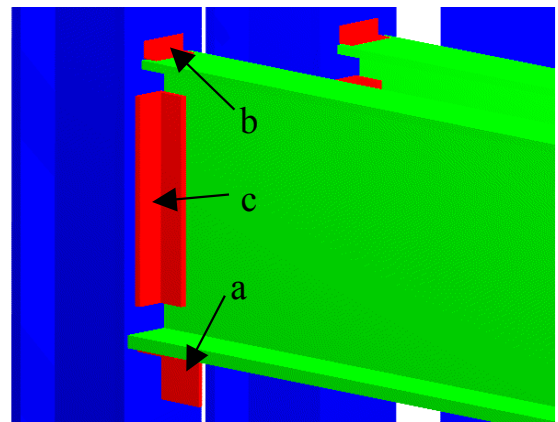


Figure 1: Design of soldier-pile tremie-concrete slurry wall and composite steel-and-concrete roof system



Figure 2: Photo of as-built soldier-pile tremie-concrete slurry wall and composite steel-and-concrete roof system

## Constructability Problems

Uncertainty refers to one's lack of knowledge about the value a parameter can take. Variability describes a range of values a parameter can take. Known variability is the range one believes a parameter can take. The known variability in dimensional tolerances (DT) of the soldier piles resulted in tight coupling of the roof installation and connection (RIC) operation to the roof fabrication operations and the predecessor and successor activities. Uncertainty about the DT of the piles increased the variability in the scope of work, duration/timing, quality, resource assignment, flow path and sequencing and the cost and time of the RIC.

The connection tolerance of 1.9 cm ( $\frac{3}{4}$ "") to 3.8 cm ( $1\frac{1}{2}$ "") between the face of the pile and roof girder combined with the known variability in the pile position required a detailed survey, once the face of the pile at the roof elevation was exposed, that was sent to the roof and SIP form fabricators. This coupled the manufacturing of the roof and decking tightly to the excavation and exposure of the pile faces that preceded the RIC. The roof girder fabricator then required two weeks to make the final cut on the roof to match the pile, paint the end, bend the cleat angles to match the pile, and ship all to site. This lead time ruined efficiency on site because crews and equipment had to remobilize if and when the girders arrived two weeks later. It also increased wall movement as the roof girder was part of the wall support. A main design concern had been to limit wall movement because it might affect surrounding buildings. The sensitivity to wall movement also limited the amount of un-braced wall that could be exposed at once to take measurements to fabricate the adjacent girders, meaning more delay in all operations. So now, roof fabrication is on the critical path, the variability of fabrication is added in series with the other operations, thus increasing the overall uncertainty for the project duration.

Another problem was the design only allowed for a tolerance of 0.6-degrees of horizontal pile rotation. The piles were to hold in place by resting them against the bottom of the excavation. However, the excavation often went deeper, both due to imprecision of excavation and to poor bedrock (requiring excess excavation), leaving the piles short of the bottom. The two piles installed as a connected pair could swing 2 degrees horizontally before hitting the sides of the hole. The design also specified the roof girder to be plumb. Even if the girder did not have to be plumb there is no guarantee that the pile on the opposite wall was rotated the same direction. With a 2-degree horizontal rotation, for roof girders over 1.2 m (4') tall, the problem shown in Figure 3 resulted. The cleat angle does not fit on the pile and cannot accommodate the required 1.9 cm ( $\frac{3}{4}$ "") fillet weld (a) between the angle and the face of the pile. The fix was to trim the clip angle to accommodate the weld. Though the fix was simple and inexpensive on the surface, the ripple effects added cost, time, and uncertainty.

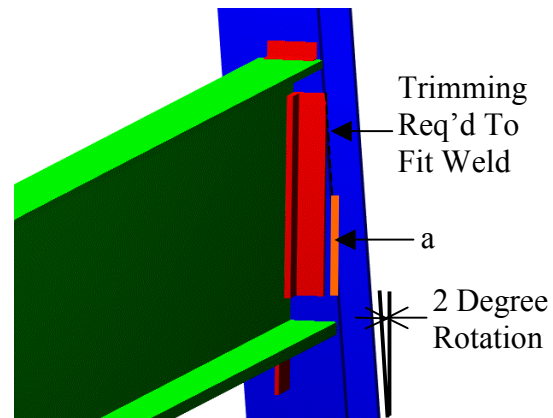


Figure 3: Inconsistency in the as-designed tolerance constraints for the roof wall interface

## Examples of Impacts

Tommelein (2000) highlighted the need to acknowledge, represent, and understand the effects of variability and uncertainty on successful integration of product and process development. Understanding is the first step towards reducing uncertainty and designing robust systems. Tommelein identifies four examples of product uncertainty, configuration, dimensional tolerances, dimensional variation, and location and layout and five examples of process uncertainty, scope of work, duration and timing, quality, resource assignment, and flow path and sequencing. The following are examples of impacts on process uncertainty resulting from the mismatch between the dimensional tolerances and the process capability:

**1. Scope of Work:** A technical issues meeting between the designer, construction manager (CM), and general contractor (GC) was required. Each occurrence of the problem required detailed measurements by the survey crew, engineering calculations by the designer of record (DR), documentation by the GC, CM, and DR, mobilization and demobilization to the work area by the crew and equipment, steel cutting and steel preparation work by the ironworkers, and quality inspection by the GC and CM. Given it was unknown when this condition would occur the scope uncertainty was increased.

**2. Duration and Timing:** At the first occurrence work was interrupted to investigate the problem. The uncertainty in duration of the RIC operation was increased given the possibility of additional work. The increased work scope also affected the duration of sub-processes within the RIC operation by interrupting the normal flow and sequence of sub-processes, decreasing productivity in the standard work. The added uncertainty in the RIC operation affected planning for follow-on activities, increasing overall duration.

**3. Quality:** Quality may be compromised by cutting the clip angle in the field. Removing some of the clip angle reduces excess capacity and adds eccentricity into the connection. Field cutting and angle preparation may not match the quality of cutting done in the shop. These factors add up but may or may not affect quality.

**4. Resource Assignment:** The additional durational uncertainty and resource requirements for the increased scope in work add to the uncertainty in resource assignment. When the problem occurs, work on a fix cannot proceed until approval is gained. Ironworkers were reassigned to other tasks during that time and were not always available when approval was received; further impacting the duration to complete the connection and forcing follow-on crews to occasionally sit idle.

**5. Flow Path and Sequencing:** Uncertainty in the scope of work, the subsequent need to assign ironworkers to other tasks while awaiting approval means that the optimal sequence of work performed in the area of the RIC operation may change. The flow path for access and materials to complete the RIC operation once approval is obtained may have changed. Further excavation may have occurred below the connection requiring access from above instead of below. This increase in flow path and sequence uncertainty further impacts scope resource needs and durations.

## Matching Tolerances to Process Capabilities

Tolerances specified for the pile orientations were tighter than the process of slurry-wall pile installation could achieve. So even when designers check or specify tolerances that accommodate the assembly and connection constraints, the process needs to be checked to ensure it can meet the tolerances. Figure 4 represents the possible orientations of the pile based on the pile installation procedure. The analysis illustrates that the process capability is neither well matched to the design tolerances, nor more broadly to the assembly constraints in this case compounding overall process variability and uncertainty. Structural design principles dictate that design values are chosen from the worst case 5% of the variability in the distribution of material properties and loads (Holmes and Martin 1983). Accordingly, the tolerance specified in the design should accommodate 95% of the variability in the process capability, in addition to accommodating assembly and connection constraints. Using process capability data, it is possible to analyze a design to match the design tolerances with the process capabilities, and redesign one or both to try to minimize the effects of dimensional tolerances from subsequent operations.

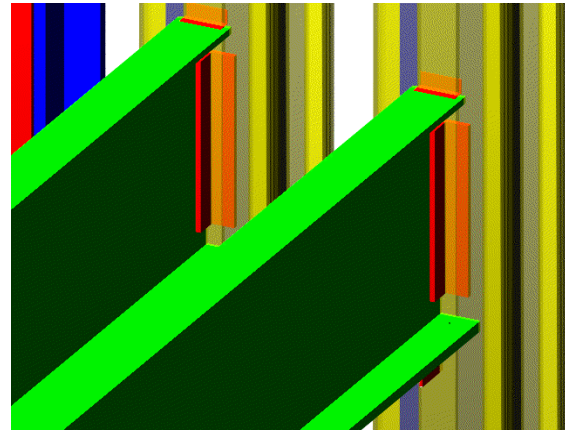
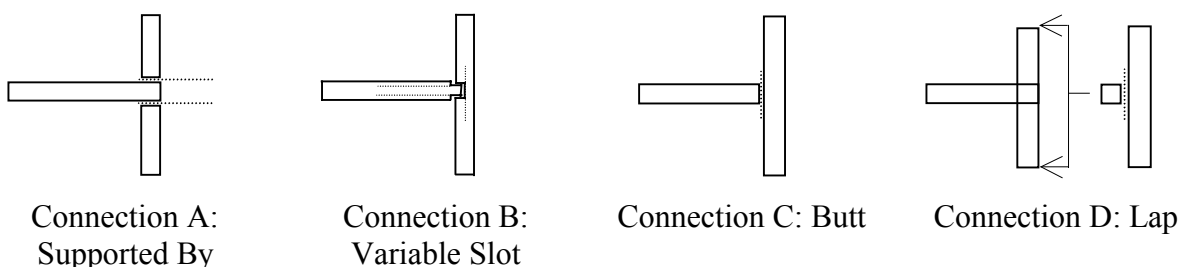


Figure 4: Effect of pile installation process capability: Connection C, Original Assembly Design

Alternative assembly/interface options between the wall and the roof were investigated from a list of conceptual types of connections (Figures 5). Only connections C and D pass preliminary evaluations based on project constraints. Connection C results in designs similar to the original design (Figure 1). Connection D puts the roof girder adjacent to the piles. This creates additional steps in the slurry wall process because something would be needed to transfer the horizontal load between the roof and the pile but is still feasible. With the model of the process capability for the pile, assuming equal likelihood of all positions, the reliability of both connections was tested. Connection D was more reliable. This demonstrates the possibility of designing to accommodate process capabilities. See Milberg et al. (2002) for further detail of the case and methodology. Tsao et al. (2000) present a similar methodology, work structuring, which focuses mainly on process changes instead of product changes.



Figures 5: Alternative Roof to Soldier Pile Assembly Concepts

## Conclusion

The case study illustrates potential impacts resulting from lack of consideration for process capabilities and tolerances. A methodology was developed for evaluating the constructability of a design in relation to the match between process capabilities and tolerances. Constructability in AEC has similar goals to DFM in manufacturing, to apply knowledge about process to product design in order to achieve project goals, but constructability practice and tools today still rely on rules of thumb or expert knowledge much as the manufacturing industry did in its early days. Significant cost reductions and quality improvements in manufacturing have resulted from the use of detailed process capability data in regards to tolerances and other parameters, combined with an understanding of how they contribute to overall project goals.

Unlike manufacturing, process capability data can be hard to collect and use in AEC systems, as each project tends to be unique. For this reason the data must be characterized so that it can be adapted to individual projects. Further research is required to determine what standard construction process capability data will look like and how much and what type of input is required to adapt it to each project, but the need for such data is clear. Several tools being developed for construction process selection, field data collection and characterization may prove useful in this regard. In addition, the AEC industry needs to better develop means to account for tolerances through mockups, first run studies, tolerance analysis techniques, or virtual prototyping (extensions of CAD capabilities as shown here). Process decisions cannot be made based on point representations or expected values but require an evaluation of the reliability of the process to achieve acceptable performance, and the penalty incurred when performance falls outside the acceptable range. A new paradigm of design can be implemented where AEC systems are designed to accommodate construction process capabilities. The authors speculate that this can result in benefits similar to those seen in other industries.

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