Using Rapid Prototyping in Structural Engineering Analysis of Steel Connections

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Abstract

The purpose of this research is to explore the use of rapid prototyping to assist with the structural analysis of steel connection design. Structural analysis is an essential aspect of engineering design; various structural analysis techniques lead to enhanced designs, as well as failure prediction and prevention. In-house steel connection testing requires acquisition of steel, construction time and labor, and destructive testing which can be a lengthy and costly process. Rapid prototyping (RP), or additive manufacturing, creates prototypes and models from 3D Computer Aided Drafting (CAD) software using various plastic resins and powders. Rapid prototyping would not eliminate steel connection testing altogether, but prototypes would highlight design flaws and allow prompt revisions in design without needing to reorder steel and wait for fabrication. This research explores the possibility of using rapid prototyped models in place of actual steel parts for the testing of structural components. In order to accurately use rapid prototyped components in connection testing, a relationship needs to exist between the material properties of various plastics and steel. This research compares stress-strain curves and moduli of elasticity, found via tensile loading, of various plastics and steel. Finite element analysis was done to locate stress concentrations in test specimens. RP would not replace steel connection testing entirely, only the iterative steps leading up to the final connection configuration.

Keywords: Rapid prototyping, structural engineering analysis, material properties

1. Introduction:

Steel connection design can be a time-consuming, costly, iterative process. If an uncommon connection needs to be designed, stress concentrations may be unknown and stress analysis will need to be done in order to find possible failures. If the connection needs to be physically tested, the steel parts will need to be ordered, there will be a lead time for the parts to be manufactured and shipped, and finally assembled, which can be labor intensive with any bolting or welding required. Then, if a design flaw is discovered, the design will be modified and the process will be reiterated.

This research examines using rapid prototyping in structural engineering analysis, particularly to streamline in-house connection design. The turnaround time of rapid prototyped parts would be hours or days compared to weeks, and the correction of a design flaw would be a correction on a 3D computer software model. Shipping and assembly wouldn’t be necessary if the rapid prototyping is done in-house. Rapid prototyping would not replace steel connection testing entirely, only the iterative steps leading up to the final connection configuration.

2. Objectives:

The purpose of this research is to correlate RP plastics to steel, and find one plastic that most closely resembles the material properties of steel. Then a connection could be rapid prototyped using that plastic. Non-destructive testing could be used to locate stress concentrations, which would indicate possible failure locations. The RP plastic would have strengths that are a fraction of that of steel, so scaled forces would be applied to the connection. Testing of the properties of the plastic would determine what the scaling factor would be. Mechanical properties are an important aspect of rapid prototyped parts; however there are few research publications to determine the properties of RP materials[1].

3. Background:

For steel connections to be modeled out of rapid prototyped plastics, a relationship needs to exist between the materials. Steel properties are well known and well documented, while plastic materials are highly variable. To properly experiment with plastics in order to obtain material properties, an understanding of strengths of materials is required.

3.1. stress-strain relationship:

In 1678, Robert Hooke first reported a linear relationship between the amount of force or load applied to a material and its physical deformation. The amount of deformation is dependent on the material's properties and the specimen's dimensions. Dimensional effects are normalized by dividing the force (F) by the initial cross-sectional area (A) being loaded. Equation(1) is the stress (σ) in a specimen:

$$\sigma = \frac{F}{A} \tag{1}$$

Dividing the deformation (change in length, ΔL) by the original length (L_0) is defined as the strain (ε) in the specimen, given by equation(2):

$$\varepsilon = \frac{\Delta L}{L0} \tag{2}$$

A graph of stress versus strain (Figure 1) gives a considerable amount of information about the material, including the modulus of elasticity, the yield strength, and the ultimate strength[2].

In order to find an accurate factor, a relationship needs to exist between the chosen plastic and steel. The key property considered in this research was the modulus of elasticity. Almost all materials have a recorded modulus of elasticity or a range of values for the modulus. The modulus of elasticity for steel is commonly taken to be 29,000 ksi. However, due to the variables in plastics from build conditions to test conditions, accurate and consistent moduli values are difficult to find. The stress-strain qualities of plastics are greatly dependant on factors such as rate of stress application, temperature, and history of the specimen. However for most materials, in low stress regions, a linear stress-strain relationship exists, and a tangent to the linear portion can be used to determine modulus of elasticity[3].

The modulus of elasticity (E), particular to individual materials, is the proportional constant between stress and strain of an axially loaded member, given in equation(3). This constant holds for homogenous, isotropic, elastic materials[4].

$$E = \frac{\sigma}{\varepsilon} \tag{3}$$

As strain increases, the linear relationship may cease to hold for many materials, terminating at the proportional limit.

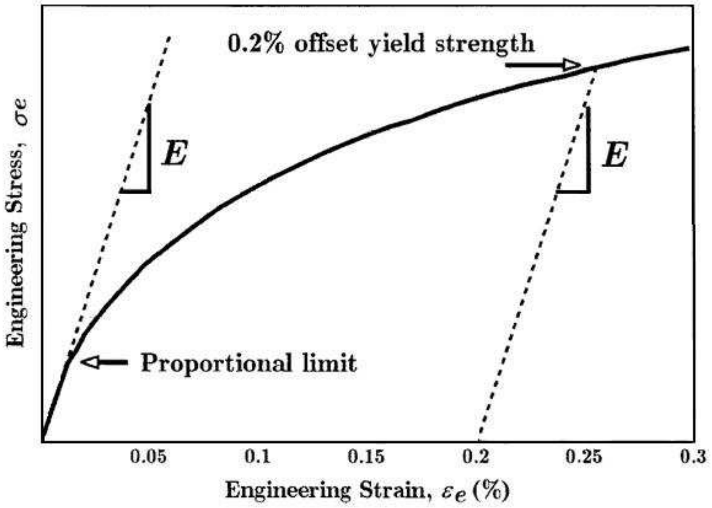

Figure 1. Low-strain region of an engineering stress-strain diagram for a ductile material[5].

4. Methodology:

This research involved comparing the material properties of various RP plastics through physical specimen testing. To compare the materials, the geometry of the test specimen had to be determined. The testing apparatus available put restrictions on specimen geometries. The geometries were also subject to the restrictions of the maximum build areas of the rapid prototyping machines, which wasn't an issue in this case. It is also necessary to be familiar with the various rapid prototyping processes, since the processes influence final properties of the plastics.

4.1. rapid prototyping process:

Rapid prototyping, also called additive manufacturing, uses plastics or other RP materials to create prototypes or models through an additive layering process. RP machines build prototypes from 3D computer models that are converted into .STL files. An .STL is a neutral interface that breaks geometries down into triangles. Then, the geometry is sliced into 2D layers which form the cross-sections that build up to form the model or prototype[6].

Table 1. rapid prototyping machines (bold) and respective plastics tested [7]

SLA®-5000 (*3D Systems*)	**DTM Sinterstation 2500^{plus} (*3D Systems*)**	**FDM Titan (*Stratasys*)**	**Spectrum Z510 (*Z Corporation*)**
WaterShed® XC 11122	DuraForm® Polyamide (PA)	Acrylonitrile Butadiene Styrene (ABS)	ZP® 131
RenShape® SL 7870	DuraForm® Flex	Polycarbonate (PC)	
Accura® 25		Polyphenylsulfone (PPSF)	

While several types of rapid prototyping technologies were used, this research focuses on the stereolithography apparatus (SLA) and the selective laser sintering (SLS) processes. SLA utilizes liquid photopolymers and a UV laser to create a 3D model by layering cross-sections 0.003 in. - 0.005 in. in thickness. A platform is located just below the surface of a vat of liquid resin, and a solid state UV laser traces the cross-section at that layer in the liquid polymer, which cures the resin. SLA uses supports that secure the model in place during the build, and allow for easy removal of the part. Post-processing is generally required, which includes a UV post-cure and surface finishing. SLA is considered the most accurate of RP machines and is capable of creating intricate geometries [8].

In the SLS process, plastic powders are sintered together by a carbon dioxide laser that heats the powder. The part is built on a center platform on a piston and is lowered a layer at a time, approximately 0.004". Rollers on two pistons on either side of the platform spread powder over the part bed at every layer. The carbon dioxide laser is focused by mirrors and directed to the part bed, where it traces the model's cross-sections in the powder to create the model. Parts can be stacked in a SLS machine since they are supported by the surrounding powder and they do not require supports. SLS models have high quality mechanical properties and high resistance to heat and chemicals[9]. SLS parts were built at a laser power of 35 W for this research. Scan speed and energy density were not specified but were held constant.

4.2. experimental process:

ASTM E8/E8M-08 *Standard Test Methods for Tension Testing of Metallic Materials* is used to determine yield strength, ultimate or tensile strength, elongation, and reduction of area. A test specimen of small cross-sectional area is subjected to a tensile loading. The specimen is fabricated with the intended breaking point in the center, where the cross section is reduced. This is to ensure fracture along the gage length of the specimen.

The cross-section can be a variety of shapes including plate, sheet, round rod, wire or tube; round rod specimens were used in this research. The geometry used is shown in Figure 3. The specimen is placed in an ultimate tensile testing apparatus (a Tinius-Olsen® ultimate tensile testing apparatus) and held in place with grips that are located such that only uniaxial tensile loading is on the test specimen and bending is not introduced[10]. Section 7.6.1.2 of ASTM E8 describes speed of testing in terms of rate of straining. It also states that for machines without strain-pacing devices, strain rate may be determined using a timing device in conjunction with a known strain increment[11]. The specimens were loaded at a strain rate of approximately 0.02 in/in/min. An extensometer using a linear variable differential transformer (LVDT) measured the deformation along the minimum diameter of the specimen.

The specimens tested were designed to ASTM E8/E8M, rather than ASTM D638 *Standard Test Method for Tensile Properties of Plastics,* for direct comparison reasons. Since the steel specimens were built in accordance to ASTM E8/E8M standards and had established dimensions, the plastic specimens were modeled after the steel specimens in order to have the same volume, surface area, and dimensions. This would allow for a direct comparison of material properties devoid of geometrical disparities. Since rapid prototyping builds though additive layering, each plastic tested was built in two orientations, shown in Figure 2, to determine effects of build orientation, or degree of isotropy. Steel is isotropic; isotropy describes a material in which its material properties are constant along the axes of the specimen. Materials with properties which are dependent on direction are anisotropic, thus a plastic with maximum isotropy is considered most applicable for this research.

In addition to being isotropic, steel generally has ductile tendencies in tension. Ductile materials can undergo appreciable amounts of plastic deformation before failure.[12] A visible form of this phenomenon is necking, a reduction in cross-sectional area in regions of high strain localization.

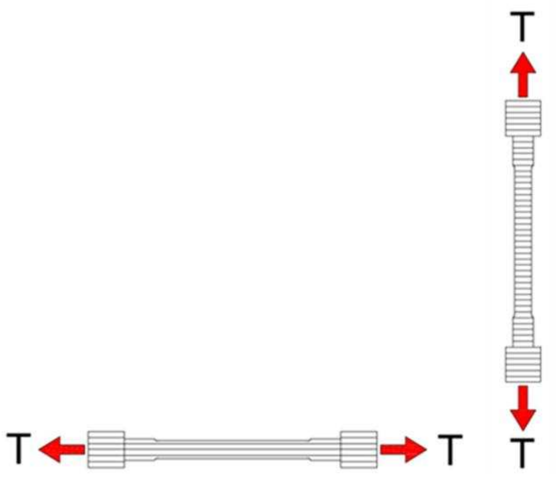

Figure 2. Left: 0° build orientation; right: 90° build orientation.

Figure 2. Specimens built horizontally on an RP machine were designated as 0° builds and specimens built vertically on were designated as 90° builds. Horizontal lines indicate build layers.

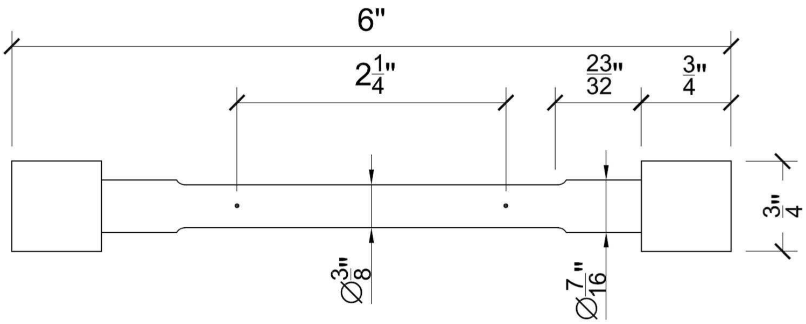

Figure 3. Dimensions used to create RP tensile barbell specimens.

5. Data Analysis and Results:

Initially, one 0° build and one 90° of each plastic available was tested to eliminate plastics that clearly did not relate to steel properties early on in the research. Due to the extreme elongation and the near void modulus of elasticity of the DuraForm® Flex, it was eliminated from further testing. The ZP® 131 exhibited highly brittle failures and very low strength and thus was eliminated. All three of the fused deposition modeling (FDM) plastics produced higher strengths and more linear stress-strain relationships in 0° build orientation and considerable poorer results in the 90° orientation, implying that the materials were highly anisotropic, and therefore would not be applicable. The remaining SLS plastic (DuraForm® PA) and the three SLA materials had the most promising trial results. Five more specimens of each of these plastics in both directions of build were tested and are referred to as full experiment specimens in this research. During the full experiments, the ultimate and rupture (failure) forces were recorded. From the stress-strain graphs, modulus of elasticity (E) and yield strength (σ_y) were calculated. A 0.02% strain offset was used to determine yield strength. Statistical analysis was conducted on results.

Table 2. yield strengths and moduli of elasticity calculated for SLA and SLS tensile test specimens, reported as a range of minimum to maximum values

Material of Specimen	Build Orientation	Yield Strength, σ_y [ksi]	Modulus of Elasticity, E [ksi]
WaterShed® XC11122	0°	5.169 - 6.481	374.78 - 411.52
	90°	4.834 - 6.937	362.54 - 372.61
SL 7870	0°	1.436 - 4.834	132.98 - 202.84
	90°	0.997 - 1.765	99.73 - 169.03
Accura® 25	0°	3.725 - 4.361	218.23 - 261.41
	90°	4.112 - 4.767	271.58 - 293.83
DuraForm® PA	0°	3.804 - 4.713	230.06 - 262.08
	90°	3.746 - 4.109	259.32 - 337.36

5.1. material characteristics:

Each material had unique characteristic results. The WaterShed® had the highest strengths and moduli of elasticity. Since the plastic-to-steel correlation would only hold true in a predetermined stress range, high strength of a plastic (while not outlined as a success criterion) would allow for larger stress ranges in which to accurately test the connection. WaterShed® also possessed the most ductile failures, with visible necking (thinning of the material at failure location prior to fracture).

The SL 7870 specimens had the most geometry failures - fractures at grips and fillets. Geometry failures result in scattered data, so averages do not provide accurate representations of the results.

The Accura® 25 plastic was distinct in that it had higher strength in vertical build orientation. Generally, materials with layers or a grain will have higher strength when the force applied is parallel to the grain. The Accura® 25 was the only material tested that reacted reversely.

DuraForm® PA had the largest difference between build directions using difference of averages. Also notable is the fact that the trial builds of PA had much more necking and ductile failures than the later full experiment specimens. This may be because the machines were build on different machines or were build with different settings, such as scan speed, energy density, part bed temperature, or other processing factors.

5.2. statistical analysis:

Two types of statistical analysis were conducted on the full experiment results. To compare moduli of elasticity of 0° against 90° builds of each plastic individually, 2-sample test of means t-tests were done using the assumption of unequal variances and a confidence interval of 95%. To compare moduli of elasticity of all plastics in both build directions simultaneously, ANOVA (Analysis of Variance) was used. ANOVA is a statistical method that compares multiple population means. The statistical analysis was performed using Minitab® 15.1.0.0 and the readout is shown in Figure 4 and 5.

Table 3. estimates for difference and P-values per full experiment plastic from Minitab statistical readout

Material of Specimen	Estimate for Difference	P-value
WaterShed® XC11122	27.79	0.029
SL 7870	30.0	0.166
Accura® 25	-35.2	0.019
DuraForm® PA	-39.7	0.43

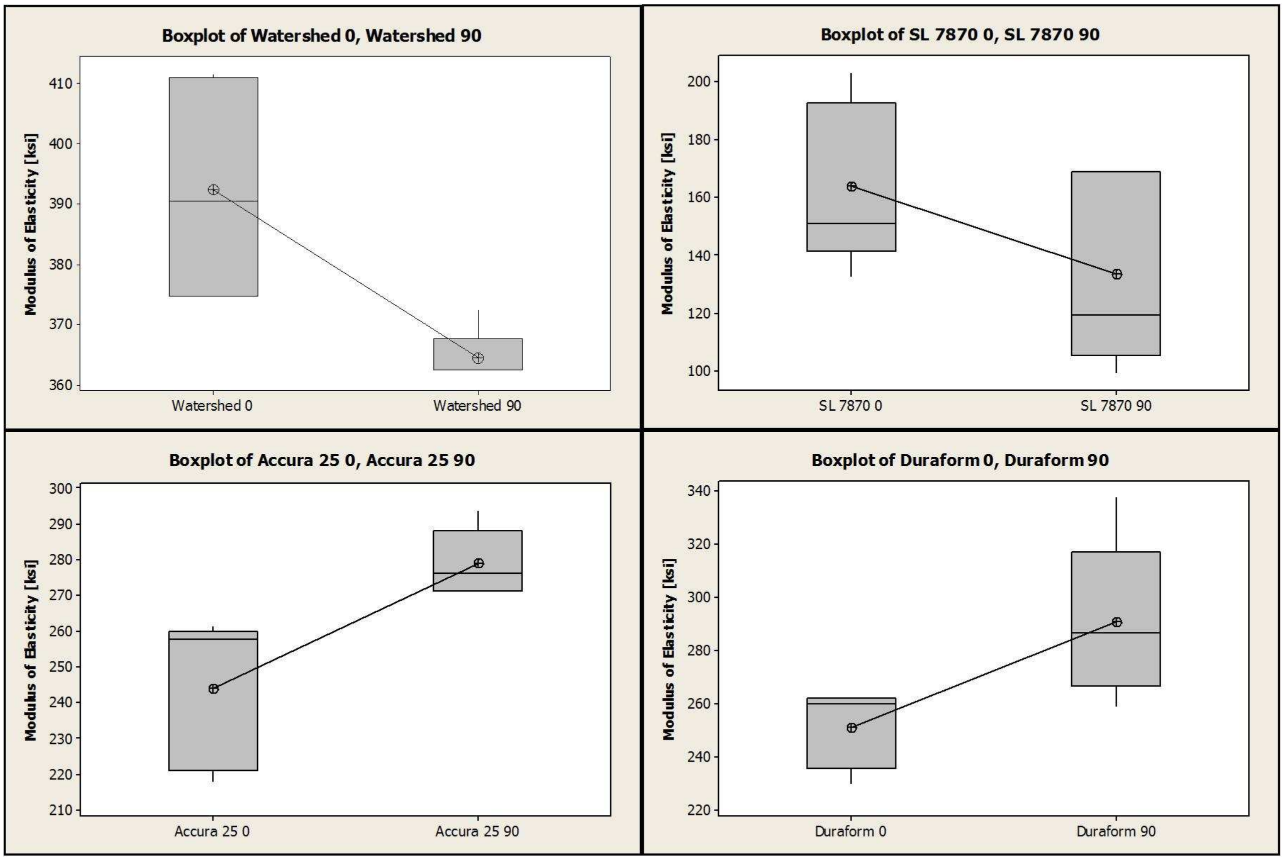

Figure 4. 2-sample t-test boxplots comparing moduli of elasticity of 0° and 90° builds for each plastic.

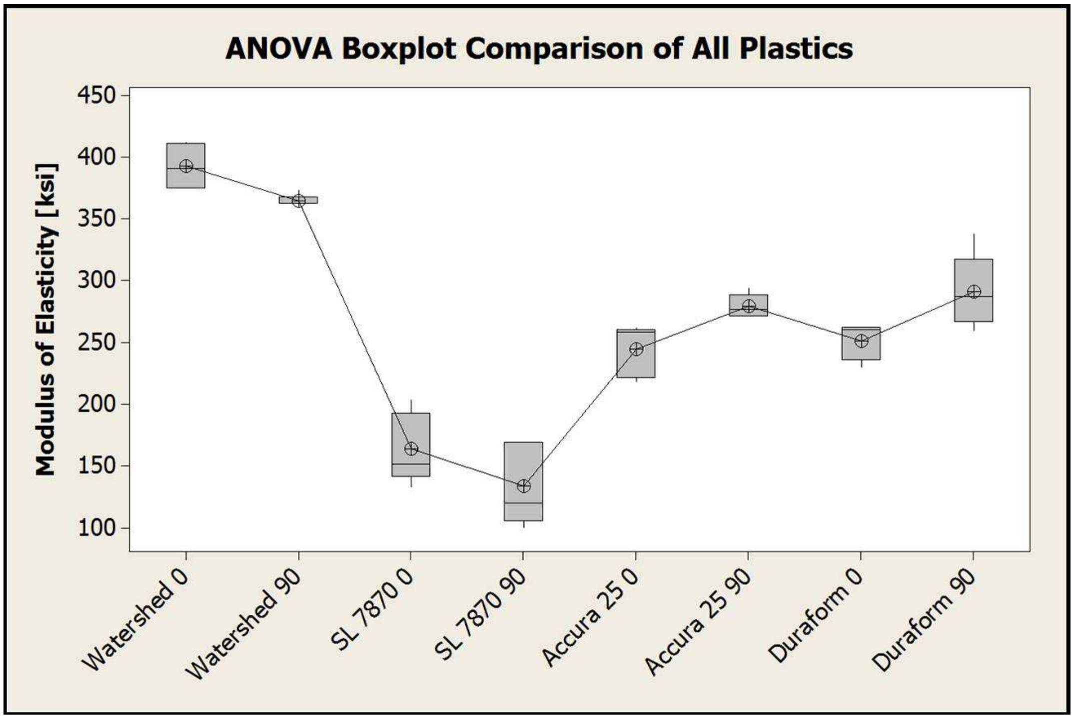

Figure 5. ANOVA boxplots comparing moduli of elasticity of 0° and 90° builds of full experiment plastics.

The WaterShed® was the most consistent per direction, but with a P-value of 0.029 ($P < 0.05$), there is enough statistical evidence to conclude a substantial difference between the moduli of each direction exists. The statistical analysis also suggests the SL 7870 is the most isotropic, having the most overlap in the boxplots and the only P-value greater than 0.05. However, the larger data ranges are due to the scattered data resulting from erratic geometry-type failures. P-values determined for both the Accura® 25 and the DuraForm® PA had statistical conclusions that a substantial difference exists. These differences imply that the materials are not isotropic, and therefore not suitable for steel connection modeling.

6. Conclusion:

Without further research, an ideal plastic cannot yet be chosen. The plastics tested displayed a variety of qualitative properties, including ductility and brittleness, isotropy and anisotropy. While SL 7870 is statistically the most isotropic, high variance in results due to geometry-type failures prevents the researcher from selecting this material for rapid prototyping connection modeling.

If a plastic had been chosen, the next research step would be to calculate the scalar multiplier for correlating plastic to steel. A ratio of the RP modulus to the steel modulus would give the reduction multiplier. Then, stress results would need to be verified. Finite element analysis was conducted to locate stress concentrations. A physical analysis would be used to verify stress patterns, such as photo stress analysis. Photo stress analysis is a non-destructive testing technique based on the concept of photo-elasticity. The photo stress analysis would show potential high stress concentrations that could be designed for structurally. Forces reduced by the scalar multiplier would be applied to the rapid prototyped connection model and compared against a steel connection with non-reduced forces to verify the correlation. Verification or disproval of a true plastic-to-steel correlation would complete this research.

6.1. future research:

Over the course of the research, additional factors arose that should be considered in future research. The rapid prototyping process has a large influence on the final strengths and moduli of the materials. RP builds should specify as many variables as possible to be able consider and determine the affects of the variables and to have consistent builds. When possible, specify, or take note of scan speed, laser power, energy density, part bed temperature, machine built on (if multiple machines of same type). Also, post-processing, such as UV exposure time, of rapid prototypes affects final properties. These variables should be taken into consideration early on in future research of rapid prototyping material properties.

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