Design and Analysis of Weldments

An Online Continuing Education Course for Engineers

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Design and Analysis of Weldments

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1. Learning Objectives:

- Design requirements for welded steel structures
- Design approach and guidelines for welded steel structures
- Types of welding for steel structures: advantages and disadvantages
- Design procedures for welding steel structures
- Base metal properties for steel
- Component preparation for welding
- Strength of welded joints
- Weld design for impact loading
- Weld design for fatigue loading
- Fatigue design guidelines for weldments
- Vibration control for weldment design
- Damping considerations for weldment structures

2. Steel Weldment Requirements

The present-day highly complex steel-welded structures for machinery parts are designed not only for cost reduction and ease of manufacturing but also for higher stiffness, longer fatigue life, and longer operating life. Weldments are used in machinery parts, bridges, structural building columns, boilers, automobiles, and many other applications where cost, quality, and reliability are essential to maintaining high customer satisfaction. Improvements in welding process quality and productivity have resulted from advances in welding technology, electrode quality, positioning fixtures, and automated welding. Moreover, heavy steel plates can be rolled to bend the corners using heavy rollers and presses. Integrating forming into the welding process has significantly improved welding quality, cost, and efficiency. The appearance of the welded structures has improved significantly. Welding is now considered a superior process for manufacturing machine parts. Because of its high design flexibility, welding is often used in place of casting.

Nevertheless, designing a welded structure is substantially different than casting design. IA casting should not be converted into a welding structure; welding structures should be designed separately. More often than not, bolted structures are also converted to welded structures. In general, casting, bolted, or riveted structures should not be directly converted to welded structures for various reasons, as mentioned later in this chapter. The choice among welding, bolting, riveting, and casting will primarily depend on production costs. Weldment design should always be treated separately, rather than converting cast or bolted structures to welding. Cost and ease of manufacturing are the ultimate criteria for selecting welding over casting or bolting. “Welldesign” is different than “Casting design.” Welding, casting, or fastening can provide rigidity, static and fatigue strength, and resistance to vibration and impact loading. The designer must select the process that offers the greatest flexibility, the highest performance, the lowest cost, and the best quality. In my experience, for low production and high flexibility, welding has always been the better option. The primary objective of this chapter is to help design engineers produce low-volume parts at the lowest possible cost and highest quality.

During my machine design career, I designed steel welding for bases and housings for machine tool components. I had very few occasions to design cast-iron structures rather than welded structures. Steel weldments provide very high productivity and accuracy at minimal cost. For such steel weldments, the lowest possible stiffness can be achieved at the lowest possible weight, with the shortest possible production turnaround time. Any highest quality machine, such as machining centers, grinders, fine boring machines, etc., has to satisfy the following **design requirements** to machine or produce parts with the highest surface finish:

- Highest stiffness to resist deflection and bending
- Lowest possible weight to increase resonant frequency to operate at the highest possible speed to produce the best possible surface finish
- Lowest possible weight per unit volume to reduce bending due to gravity loading
- Highest possible resistance against impact loading during machining operations
- High damping possible against shock loadings
- Minimum machine deformation against gravity loading
- Maximum resistance against machine deformation over a long time
- The highest possible strength of the structure
- Design Flexibility
- No porosity to prevent hydraulic or water leakage

The following requirements for a steel weldment for a machine tool are the **manufacturing requirements**, as mentioned below:

- Low Investments for machinery, jigs, and fixtures
- No fixed or variable costs for core, pattern, etc.
- No surface preparations for further processing, such as painting, etc.
- Better Surface Finish
- No environmental issues
- Low volume production
- Easy and consistent quality control
- Easy repairs of the components, if necessary
- Smaller lead time

In addition to the above requirements, machine tool components should have enhanced **base metal property requirements** at the minimum possible cost, such as

- Ultimate strength

- Higher Yield Point
- Higher Rupture strength
- No porosity, shrinkage, permanent deformation, distortion, etc.
- Higher joint damping

Machine tool materials also have some **supply management requirements.** When production volume is very low due to stringent competition and market demand, steel has advantages over casting and other materials, as mentioned below:

- Availability
- Cost Uniformity
- Availability of different forms and shapes to suit complex designs
- Ease of design changes
- Ease of fabrication
- Ease of machining, forming, and rolling, if necessary

Steel weldments meet most of the above requirements and offer advantages over castings and other materials. In general, design engineers need experience and education to design efficient welded structures. Welding is a fusion process for permanently integrating similar metals using electrodes. There are some disadvantages to this welding process. They are:

- Permanent deformation or distortion of structural elements over time due to heat
- Use of costly and complicated fixtures during welding
- Low fatigue life due to residual stress locked during welding
- Non-uniformity of the welding process during manual operations
- Repair is time-consuming and costly
- Strength depends on the type of welding
- Misalignment between components during welding due to the heat generated during welding
- Joint strength is dependent on design
- Analysis in the weld area is highly unreliable and unpredictable
- Welding among dissimilar materials is highly unlikely and very difficult
- Welding efficiency depends on the base metal properties
- Quality variations from part to part due to non-uniformity during welding
- Machining in weld areas is challenging

3. Weldment Design Approach

During weldment design, the design engineer has to consider the following aspects at the outset:

- Selection of types of materials and cross-sections for an effective welding process
- Selection of structural sections for the highest efficiency and productivity

- Analysis methods to select sectional areas to achieve strength and life requirements
- Testing methods to verify strength and life
- Quality control is desired for the structure
- Size and location of reinforcements, gussets, and stiffeners for structural rigidity
- Cost and volume of production desired

The most critical steps in design are the analysis of the structural strength of the elements. Randomly selecting material types and cross-sections yields a very heavy structure, leading to higher costs and inefficiencies. Previous experience may help to some extent, but relying solely on experience and the "Rule of Thumb" for such selection will make the structure inefficient and costly. Selecting material sections at random will increase the weight, thereby increasing fabrication, welding, and material-handling costs, as well as fabrication time. To properly design welded structures, strength, life, and cost analyses must be conducted during design, and tests must be performed to verify strength and life once the prototype is built. External and internal forces must be calculated, and their effects on the weld areas must be determined. Guidelines and methods for such calculations will be provided for some structural elements for future use.

I strongly encourage designers to think about the design as a whole system. In my opinion, a progressive welding style is better: welding should start at one end and finish at the other, or top to bottom, in a continuous manner. This allows the system to expand during welding and as residual stress develops. The effects of stress on the system are minimal. The next question is how to begin designing welding structures. In most cases, welding replaces cast components. A single weldment can replace many castings. Weldments generally save time and money. The design approach could start from the previous casting or welding design. In most cases, the author has used a previous design as a starting point, and the redesign aims to reduce weight and manufacturing complexity while increasing strength. The new design should eliminate the problems and design and manufacturing issues of the old design. Sometimes, a new design blocks fresh thinking and hinders future improvements. In most cases, the new design should incorporate new features, increased strength, and lower cost to remain competitive in the marketplace. The new design must also address installation, rigidity, and vibration requirements. Weldments can weigh less than castings without losing strength.

During design, several factors need to be considered as mentioned below:

- Types of Loads on the component: Static or dynamic
- Member's material and sectional properties
- Stress and strain on the part created by loads
- Desired Life of the component
- Cost of the component

Hence, the designer must select the material and sectional properties of the components to satisfy the above criterion simultaneously. That is the challenge for the designers. The designer must select the material and section to meet the requirements for external and internal loads. There are several types of forces, moments, and torsional loadings on any component during operation. In addition, it might also experience tension and compressive forces.

The properties of the materials can be represented by several constants as mentioned below:

- Yield Point strength, $\sigma_{yp,}$ psi
- Rupture strength, $\sigma_{r,}$ psi
- Ultimate strength, $\sigma_{u,}$ psi
- Compressive strength, $\sigma_{c,}$ psi
- Shear strength, τ psi
- Modulus of Elasticity in tension and compression, E, psi
- Shear Modulus, E_s psi
- Tensile or Compressive strain, in/in
- Shear Strain, rad/rad
- Poisson Ratio, dimensionless
- Elongation or contraction, inch

The sectional properties could be represented by the following:

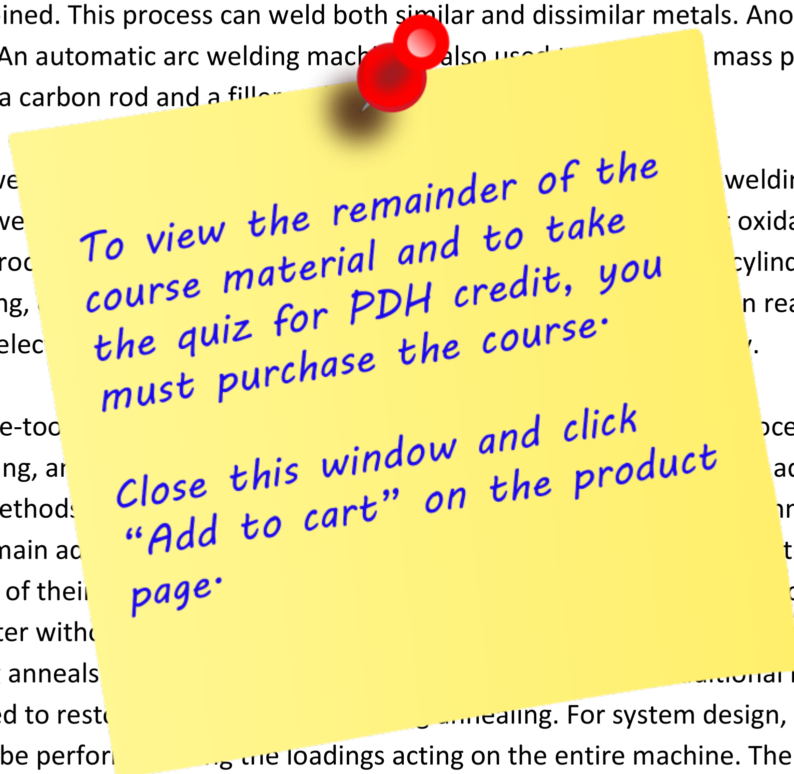
- Sectional Area, A, in^2
- Moment of Inertia, I, in^4
- Section Modulus, I/A in^2
- Polar Moment of Inertia, J, in^4
- Weight, Lbs

There are several steps required to complete a design as outlined below:

- Step 1: Requirements, including Cost
- Step 2: System Design
- Step 3: System Analysis for strength and life
- Step 4: Design Modifications, if required
- Step 5: Prototype Build
- Step 5: Validation and Verification through physical testing
- Step 6: Mass Production
- Step 7: Quality Control

There are several types of welding processes. The oldest welding process is forge welding, in which metal is formed manually on an anvil using a hammer. Blacksmiths used to use this process in the early ages. Next is resistance welding, in which an electric current heats the metals to be joined. Electric current passes through the metals, melting them locally and joining them. Electrodes are used in the process with flux. The metal's electrical resistance generates Heat. Metals melt locally and fuse. The welding is carried out progressively along the length of the parts. Spot welding is another form of

resistance welding in which a spot-welding probe joins two metals under pressure. Two plates are placed one on top of the other and pressed between two electrodes. Current passes through the overlapping plates, and the metals are joined. The plates should not exceed 3/8 to ½ inch in thickness. When the electrodes are in the form of two rollers, the process is called seam welding. Another form of welding is fusion welding, which requires no pressure to join the metals. Gas welding, or autogenous welding, uses a blowpipe in which oxygen and hydrogen are mixed to produce a flame that heats the parts to be joined. This process can weld both similar and dissimilar metals. Another welding process is arc-welding. An automatic arc welding mach
also used
mass production. An electric
arc between a carbon rod and a fill



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reinforcements are
recommended to rest
annealing. For system design, stress and strain
analyses can be perfor
the loadings acting on the entire machine. The system can be designed based on its stiffness and rigidity. I prefer designing machines based on their strength to achieve the desired life and cost for the whole machine.

In the case of design by analysis, four elements, i.e., load, stress, strain, and part details, are very important and necessary. The idea is to select the part details so that the allowable stress and strain remain within design limits. Selecting the part size, material, and shape is essential. There are several types of loading or forces and moments on any component: Tension, Compression, Moment, and torsion. A moment creates bending in a part, and torsion twists a component. Tension stretches the part, and compression compresses it. Load types can vary, including steady (static), variable (dynamic), random, or impact.

Material Properties:

- Young's Modulus in tension and compression, E
- Poisson's Ratio, μ
- Compressive strength, σ_c
- Tensile strength, σ_t