

Design of Monorail Systems

Tomas H Orihuela Jr, PE

Introduction

Overhead monorails are primarily used to lift large or heavy items and move them horizontally. Monorails can be driven manually or powered. Power-operated overhead monorails systems are typically powered by air, hydraulics, or electricity. Overhead material handling systems can be supported on single or multiple girders and can be top-running or bottom-running. Bottom-running systems travel along the bottom flange of the supporting beam and are typically associated with monorails and bridge cranes. Multiple girders and top-running systems are typically not associated with monorails but rather with overhead or gantry bridge cranes. This course covers the basic design of a monorail with a bottom-running manually-driven trolley hoist on a single girder or beam.

The course will first discuss how monorails can increase productivity and efficiency, reduce injury to individuals, produce cost savings, and even improve quality. Operation safety and inspection of monorails will also be discussed since the actual design calculation of a monorail beam is only a portion of a well-planned overhead material handling system.

The procedure presented for the design of a monorail beam is primarily based on the Crane Manufacturers Association of America (CMAA) Specification No. 74 "*Specifications for Top Running & Under Running Single Girder Electric Traveling Cranes Utilizing Under Running Trolley Hoist*". Fatigue checks and deflection limitations will also be discussed. Connections and supports will only be briefly discussed. An example of a basic monorail beam design is provided to assist in better understanding of the information presented in this course.

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Case Studies

Using monorails or other overhead material handling systems help increase productivity, efficiency, and safety while reducing costs and injury to personnel. Cases studies have shown that the use of such systems can do all of these things. Two case studies are presented below.

Case Study #1:

A company was showing an increase in employees with back injuries. Morale was low and insurance rates were increasing. Additionally, quality was an issue since 150 to 250-pound rolls requiring replacement 4 to 5 times daily were being dropped frequently by the two individuals performing the task. The addition of an overhead material handling system improved quality since rolls were no longer dropped during the replacement process, back injury to personnel was greatly reduced since lifting of heavy objects was eliminated, and, lastly, cost savings and increase in productivity were noted since the replacement process no longer required two individuals and took less time to perform.

Case Study #2:

A manufacturer of large and heavy mirrors had individuals injured often during the packaging process. Injury to personnel was occurring during the tilting and setting of the mirrors in shipping crates or when mirrors were dropped during this process. The packaging process took four individuals to complete the task. By installing an overhead material handling system, manually lifting the mirrors was no longer required, with reduced injuries. Improvement in cost savings, efficiency, and production occurred since less damage to or dropping of mirrors occurred and now only two individuals were required for the packaging task.

The two case studies presented show that overhead material handling systems could help reduce costs and injury while providing improvements in production, efficiency, and cost savings. One point to consider is insurance costs; with less individuals getting injured, the rising cost of insurance may be partially controlled. The case studies mentioned are summarized from studies found at various websites.^{4,5,6} The referenced websites provide various additional case studies showing similar results after the addition of an overhead material handling system.

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Operation Safety

The safe operation of a monorail has some impact to the design of a monorail system. Engineers need to be concerned with the operational safety of the monorails they design. To that end, engineering drawings should include some or all of the items listed below:

- maximum lift design load
- safety, impact, or load factors used
- maximum angle or load due to side pull
- method and locations of labeling stating maximum capacity, warnings, etc.

Additionally, the engineer needs to have a full understanding of how the final monorail system is anticipated to be operated. Without operations input, a monorail can be poorly designed for the intended use, ultimately resulting in the death or injury of the operator and/or bystanders.

A safety plan for the operation of the monorail should be developed with input from all parties involved: owner/specifier, engineer, inspector, and operator. The plan should incorporate, at a minimum, the following information:

- Responsibility of all parties
- Design requirements (i.e., codes, safety or impact factors, labeling, etc.)
- General safety rules
- Operational rules or instructions
- Rigging requirements
- Inspections, Maintenance, and Testing
- Record keeping responsibilities

The Department of the Interior's Safety Management Information System has a website that provides a written example of a crane and hoist operational safety plan.⁷ To assist in the development of a safety plan, this sample plan can be downloaded and is provided in a format that can be easily modified.

Operators also need to be properly trained to safely operate the monorail system. The following are methods that can be implemented to help ensure safe operation of the monorail:

- Proper training of operators and individuals in the area of use
- Use of check lists for inspection
- Scheduling of inspection (Interval based on level of use)
- Clear, unobstructed labels stating rated load on monorail beam and hoists

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The Hoist Manufacturers Institute (HMI) has created recommended practices for manual and powered hoists.⁸ The recommended practices list “Shall’s and Shall Not’s” for the operation of hoists. The documents provide valuable information and will assist in the development of an operational safety plan. A few of the items included in the recommended practices from HMI are listed below.

To avoid a potentially hazardous situation that could result in serious injury or death, the operator:

- SHALL NOT lift loads more than the rated load.
- SHALL NOT lift individuals if the systems is not rated for lifting of personnel
- SHALL NOT lift a load over people and SHALL assure other personnel stay clear of the load.
- SHALL be familiar with the operating controls, procedures, and warnings.

To avoid a potentially hazardous situation that could result in minor or moderate injury, the operator:

- SHALL avoid swinging the hook or load.
- SHALL inspect the hoist regularly
- SHALL NOT allow your attention to be diverted from operating the hoist.
- SHALL be familiar with the operating controls, procedures, and warnings.

Pre-planning

Remember the “Six ‘P’ principle”: Prior planning prevents pretty poor performance. Identifying all, or as many of, the design parameters in the initial stages of design allows for a better designed and operational system.

Some basic initial information and design criteria needed for the design of a monorail system includes:

- Design load rating or lift load
- Safety, load, or impact factors to use
- Design codes or other specifications
- Minimum clearances required
- Special requirements specific to the project
- Minimum or Maximum hook height
- Path of monorail
- Preferred method of support
- Connection types: welded or bolted
- Understanding of final use

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Part of the pre-planning process is to determine the classification of the monorail, which is required for the fatigue design check of the monorail system.

Monorail Classification

The classification of the monorail is mainly required for checking fatigue. CMAA Specification No. 74 has four (4) classifications that are based on the level of service of the system.

The classifications are:

- Class A – Stand-by or Infrequent Service – Capacity load handled during installation and during infrequent maintenance.
- Class B – Light Service – Load varies from no load to the rated load and is lifted 2 to 5 times per hour and averaging 10 feet per lift.
- Class C – Moderate Service – Lifts 50% of rated load 5 to 10 times per hour and averaging 15 feet per lift.
- Class D – Heavy Service – Lifts 50% of rated load more than 10 times per hour.

In many cases, the classification can easily be determined; however, the code also provides a table that can be used to determine the classification based on more detailed information: load classes and load cycles.

The four (4) load classes per the code are:

- L_1 – hoist normally lifts with very light loads and very rarely the rated load.
- L_2 – hoist normally lifts loads at 1/3 the rated load and rarely the rated load.
- L_3 – hoist normally lifts loads 1/3 to 2/3 the rated load and lifts the rated load fairly frequently.
- L_4 – hoist regularly lifts close to the rated load.

The four (4) load cycles per the code are:

- N_1 – 20,000 to 100,000 cycles – irregular use followed by long idle periods.
- N_2 – 100,000 to 500,000 cycles – regular use in intermittent operations.
- N_3 – 500,000 to 2,000,000 cycles – regular use in continuous operations.
- N_4 – over 2,000,000 cycles – regular use in severe continuous operations.

How the classification of the system is used for fatigue checks will be covered later in this course.

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Design Considerations

Clearances

Dimensions of the largest and heaviest items to be lifted are required in order to assure that proper access is provided along the entire path of the monorail.

CMAA provides minimum clearance requirements of 2 to 3 inches at different locations along the monorail. Use of larger clearances is recommended to account for any unknowns, deflection of other items or supporting structure in the area, and to allow for more flexibility during installation and future uses.

Support locations

Support locations are determined based on (and not limited to) the following:

- Combined axial and bending stresses
- Fatigue allowable stress range
- Deflection limitations
- Maximum beam height allowed – the span may need to be shortened if a deeper beam can not be used to reduce stresses or if deflections result in clearance problems.

The design of the monorail beam along with the supports and connections can be an iterative process. However, the design of the supports is not within the scope of this course.

Connections

Bolted and/or welded connections can be used on a monorail. The type of connection may be driven by the owner's specification, costs, and constructability. The CMAA code provides guidance for the fatigue check of a welded connection. For bolted connections, AISC's ASD and LRFD (Latest Editions) list bolt capacities for strength checks.^{1,2} For fatigue of bolted connections, AISC LRFD (Last Edition) provides some guidance. The design of connections is not within the scope of this course.

Deflection Limitation

The vertical deflection of the monorail beam shall be limited to L/450. A tighter limitation should be used if required by the project specifications. The L/450 limitation shall apply to all beams including cantilever beams. The lateral deflection of the beam should also be considered.

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Material and Structural Shapes

The most common shape utilized for the design of monorails with under hung hoists is the S-shape. The S-shape sections have narrow flange widths but also thicker flanges compared to equivalent W-shape sections. Monorails can also be designed using W-shape sections; however, the local bending of the bottom flange due to the wheel loads governs the design of the beam more often.

ASTM A36 ($F_y = 36$ ksi) is the most common material readily available for S-shape sections. ASTM A992 ($F_y = 50$ ksi) is now more common for W-shape sections. Recently, ASTM revised the A992 specification to include shapes other than W-shape; however, S-shapes are not yet readily available in A992.

Loads Defined

The loads as defined by the CMAA specification are as follows:

<u>Dead Load (DL)</u>	The weight of the monorail beam and any other fixed item supported by the beam.
<u>Trolley Load (TL)</u>	The weight of the trolley and any other equipment attached to the trolley.
<u>Lifted Load (LL)</u>	The weight of the item lifted along with all associated lift devices such as slings, shackles, spreader beams, etc.
<u>Collision Forces (CF)</u>	Loading resulting from the collision with another trolley or bumper stop. The velocity and mass of the objects are required to determine the kinetic energy released during the collision.
<u>Inertia Forces from Drives (IFD)</u>	Forces occurring during the acceleration, deceleration, and motions of the monorail.
<u>Operating Wind Load (WLO)</u>	The loading on the projected area exposed to the wind. The wind velocity at which a safe lift should be used as specified by the owner/specifier. The code states that a minimum of 5 psf loading should be used if no information is provided.
<u>Stored Wind Load (WLS)</u>	The maximum wind applied to the monorail when the system is <u>not</u> in use.

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Forces due to Skewing (SK)

Horizontal forces normal to the beam when wheels roll along the length of the beam. A table provided in the code is used to determine a factor to be applied to the wheel loads.

Additional Loads to Consider

The monorail beam should also be designed for in-line (axial) and out-of-plane (lateral) loading. AISC ASD states that a minimum of 10% of the load shall be applied in-line or longitudinally and a minimum of 20% of the load shall be applied normal to or perpendicular to the beam. The load used in the calculations should be based on the lift load and the trolley weight with all load factors applied.¹

Torsional moment caused by the out-of-plane loading should also be accounted for in the design. The moment is determined by multiplying the lateral load by the vertical distance between the beam's shear center and the centerline of the load. The load is generally assumed to be applied at the bottom flange for bottom-running trolleys; therefore, for a standard S-beam or I-beam, the distance is one-half (1/2) the beam depth. To determine the torsional stress on the beam, AISC's Steel Design Guide Series 9: Torsional Analysis of Structure Steel Members can be referenced. The stresses are determined using the section modulus of one flange only.¹⁰ The example at the end of this course will provide further guidance.

Load Factors

Load factors are used to account for such items as impact and dynamic lift situations, or to account for unknowns. The load factors discussed below are as defined by the CMAA code; however, these factors can be adjusted to account for the specific design situation being investigated.

Dead Load Factor (DLF)

This factor covers the dead loads of the trolley hoist and any associated equipment. The factor is based on the travel speed of the trolley and is determined using Equation 1.

$$DLF = 1.10 \leq 1.05 + \frac{TravelSpeed}{2000} \leq 1.20 \quad (Eq. 1)$$

where *TravelSpeed* is in feet per minute (fpm).

For a powered trolley, the minimum dead load factor is 1.10. For a trolley that is manually-driven, the travel speed is relatively low so Equation 1 is not required. A factor of 1.05 to 1.10 should be utilized to account for some unknowns such as mill and weld tolerance.

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Note that the Dead Load factor (DLF) accounts for the dead load of the beam (DL), trolley and associated equipment (TL), while the term “Dead Load (DL)” introduced in the previous section only refers to the dead load of the beam. It is important to note this distinction since the nomenclature can be somewhat confusing.

Hoist Load Factor (HLF)

This factor accounts for the motion of the rated load in the vertical direction. The factor also accounts for inertia and mass forces due to sudden impact load during lifting. The factor is also a catch-all accounting for all other uncertainties. The HLF factor is determined using Equation 2.

$$HLF = 1.15 \leq 1 + .005 \times HoistSpeed \leq 1.50 \quad (Eq. 2)$$

where *HoistSpeed* is in feet per minute (fpm).

For manually-driven trolleys, the load is typically hoisted without the use of power thereby the hoist speed is relatively low. Therefore, Equation 2 may be ignored and a minimum factor of 1.10 to 1.15 can be used.

Load Combinations

The CMAA specification requires that combined stresses be checked for three different stress levels. The three (3) load combinations requiring evaluation are:

- Case 1 – Monorail in regular use under principle loading (Stress Level 1).

$$(DL \times DLF) + (TL \times DLF) + (LL \times HLF) + IFD \quad (Eq. 3)$$

- Case 2 – Monorail in regular use under principle loading and additional loading (Stress Level 2). This is similar to Case 1 with the addition of operating wind loading and skewing forces

$$(DL \times DLF) + (TL \times DLF) + (LL \times HLF) + IFD + WLO + SK \quad (Eq. 4)$$

- Case 3 – Monorail under extraordinary loading (Stress Level 3). There are two conditions evaluated for this case.

- Case 3a – Monorail not in use and Stored Wind Load.

$$DL + TL + WLS \quad (Eq. 5)$$

- Case 3b – Monorail collision.

$$DL + TL + LL + CF \quad (Eq. 6)$$

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Allowable Stresses

Table 1 lists allowable stresses for the three (3) stress levels. The allowable compression stress listed in the table is for beam not subject to buckling. F_y noted in the table below is the minimum yield strength of the beam material.

Table 1: Allowable Stresses per CMAA

Stress Level	Axial Compression Allowable (*) F_a	Axial Tension Allowable F_a	Shear Allowable F_v	Bearing Allowable F_{br}
1	$0.60 F_y$	$0.60 F_y$	$0.35 F_y$	$0.75 F_y$
2	$0.66 F_y$	$0.66 F_y$	$0.375 F_y$	$0.80 F_y$
3	$0.75 F_y$	$0.75 F_y$	$0.43 F_y$	$0.90 F_y$

* For beams subject to buckling, the axial compression allowable stress shall be as defined by Equations 7 and 9.

** Compression and Tension allowables are also utilized for bending allowables about the major and minor axis of the beam.

For a beam subject to buckling due to compression loading, the average allowable compressive stress on the cross sectional area is defined below. For axial allowable calculations below, the larger KL/r value calculated from each the major and minor axis of the beam shall be used.

When $KL/r \leq C_c$ then

$$F_a = \frac{\left[1 - \frac{(KL/r)^2}{2C_c^2} \right]}{N \left[\frac{5}{3} + \frac{3(KL/r)}{8C_c} - \frac{(KL/r)^3}{8C_c^3} \right]} \quad (\text{Eq. 7})$$

where C_c is defined as

$$C_c = \sqrt{\frac{2\pi^2 E}{F_y}} \quad (\text{Eq. 8})$$

and

F_a = allowable axial stress (ksi)

K = effective length factor

L = unbraced length of compression member

r = radius of gyration of the member

E = modulus of elasticity (ksi) (29,000 ksi for steel)

N = constant. Use 1.10 for Stress Level 1 cases.

Use 1.00 for Stress Level 2 cases

Use 0.89 for Stress Level 3 cases.

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When $KL/r > C_c$ then

$$F_a = \frac{12\pi^2 E}{N(23)(KL/r)^2} \quad (\text{Eq. 9})$$

Interaction Equations

Members subject to combined axial and bending stress shall meet the following requirements.

$$\frac{f_a}{F_a} + \frac{C_{mx} f_{bx}}{\left[1 - \frac{f_a}{F_{ex}}\right] F_{bx}} + \frac{C_{my} f_{by}}{\left[1 - \frac{f_a}{F_{ey}}\right] F_{by}} \leq 1.0 \quad (\text{Eq. 10})$$

$$\frac{f_a}{F_{ax}} + \frac{f_{bx}}{F_{bx}} + \frac{f_{by}}{F_{by}} \leq 1.0 \quad (\text{Eq. 11})$$

When $f_a/F_a \leq 0.15$, then equation 12 may be used in lieu of Equations 10 and 11.

$$\frac{f_a}{F_a} + \frac{f_{bx}}{F_{bx}} + \frac{f_{by}}{F_{by}} \leq 1.0 \quad (\text{Eq. 12})$$

where f_a = actual axial stress (ksi)
 f_{bx} = actual bending stress about major axis (ksi)
 f_{by} = actual bending stress about minor axis (ksi)
 F_a = allowable axial stress (ksi)
 F_{ax} = allowable axial stress per Table 2 (ksi)
 F_{bx} = allowable bending stress about major axis (ksi)
 F_{by} = allowable bending stress about minor axis (ksi)
 C_{mx} and C_{my} is a reduction factor (reference CMAA specifications or AISC for additional information)

and where

$$F_{ex} = \frac{12\pi^2 E}{N(23)(KL/r)_x^2} \quad (\text{Eq. 13})$$

$$F_{ey} = \frac{12\pi^2 E}{N(23)(KL/r)_y^2} \quad (\text{Eq. 14})$$

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Local Bending of Bottom Flange

The local bending of the bottom flange of the beam or girder due to the wheel load is an often overlooked design check. S-beams are the most common shape used for monorails; however, I-beams are sometimes used. Since the flange thickness of an I-beam is thinner than an equivalent S-beam, the local bending of the bottom flange of the I-beam could control the design of the monorail beam.

The wheel load is determined using basic static analysis, where in many cases it is one-fourth ($1/4$) the lift load with load factor applied. The wheel load is generally considered to be a concentrated load applied at the center of the wheel contact with the flange (see Figure 1).

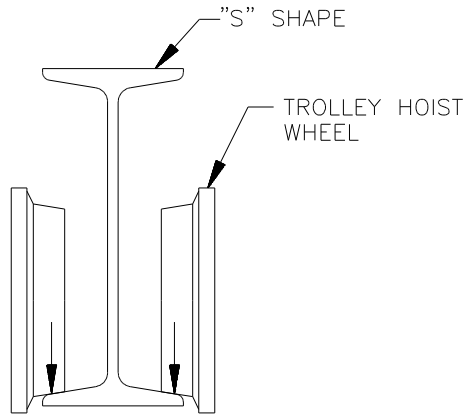


Figure 1: Wheel Contact on Bottom Flange

The CMAA code provides guidance for checking the wheel load on both an S-beam and I-beam. In addition to checking the stress caused by one wheel load, the stress between the wheels on one side of the beam should be checked. In many cases, the wheel spacing longitudinally is short so the stress from the two wheels may be high between the two contact points. Roark's *Formula for Stress and Strain* is a good reference for determining this stress.⁹

Fatigue Design

Fatigue problems occur in monorails due to the repeated loading and unloading of the system. A Class A monorail will likely not have fatigue problems due to infrequent usage. On the other hand, a Class D monorail design could possibly be governed by fatigue since its usage is very frequent.

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How is Fatigue checked?

Fatigue is checked by determining the maximum stress range encountered by the beam and checking if it does not exceed the allowable stress range. The maximum stress range is the maximum stress (fully loaded condition) minus the minimum stress (unloaded condition).

$$UR_{fatigue} = \frac{MaximumStressRange}{AllowableStressRange} \leq 1.0 \quad (\text{Eq. 15})$$

Fatigue Allowables

The CMAA code provides a table with allowable stress ranges based on two factors: (1) service classification previously discussed and (2) joint category. Six (6) categories (Category A through F) cover various conditions and connection types. Category A is the least severe while Category F is the most severe category.

CMAA Specification No. 74 provides a table listing various conditions for each category. Additionally, the code provides figures that can be referenced to quickly determine which category is applicable. Table 2 below provides an example for each of the six categories.

Table 2: Joint Category Examples

Joint Category	Situation
A	base metal of non-built-up members (i.e., standard rolled shapes)
B	base metal or weld metal in a complete joint penetration groove welded splices of rolled and welded sections of similar profiles with welds grounded and passes nondestructive testing (NDT)
C	similar to Category B except splice occurs where transitions of thickness or width where slopes are no greater than 1:2.5 ratio
D	base metal at the net section of bolted connections
E	base metal of axially loaded members with fillet welded end connections
F	fillet weld metal

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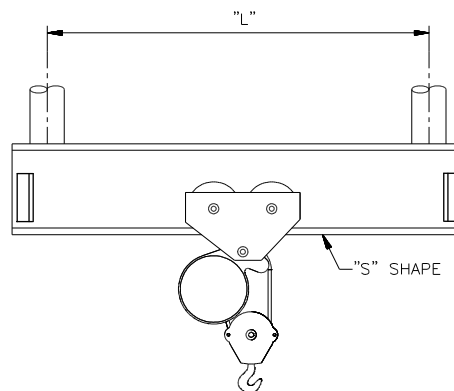
Using the service classification and the joint category, the allowable stress range can be determined. Table 3 lists the allowable stress range for each service classification for each category. On a Service Class A system, for comparison purposes, a Joint Category F has an allowable stress range of 15 ksi as compared to 63 ksi for a Joint Category A.

Table 3: Allowable Stress Range

Service Class	Allowable Stress Range (ksi)					
	Category A	Category B	Category C	Category D	Category E	Category F
A	63	49	35	28	22	15
B	50	39	28	22	18	14
C	37	29	21	16	13	12
D	31	24	17	13	11	11

Example

An existing monorail requiring recertification is located over a heavy piece of equipment. The monorail is used very rarely for maintenance or replacement of heavy components. As part of a safety plan being implemented, the owner is in need of determining the monorail beam's capacity and labeling it accordingly. The existing monorail is composed of an S10x25.4 beam spanning ("L") 11-feet between support hangers and has a yield strength (F_y) of 36 ksi. The monorail beam was not labeled with its capacity. The existing manually-driven bottom-running trolley is labeled as having a 2-ton capacity and weighs 250 pounds. The monorail is located where it is protected from the wind. For this example, the support hangers, supporting structure and connections need not be checked.



Sketch of Existing Monorail System

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Since the trolley is manually-driven, IFD and CF loads will be ignored due to the relatively low velocity. Wind loading (WLO and WLS) can also be ignored since the existing monorail is located in a protected area. Therefore, only Case 1 (Stress Level 1) needs to be evaluated; hence, Equation 3 can be modified as follows:

$$(DL \times DLF) + (TL \times DLF) + (LL \times HLF)$$

Based on the requirements, the following deductions can be made:

- The beam will be checked as a simply supported member; therefore, use $K=1.00$ in KL/r calculations.
- Dead load factor (DLF): A factor of 1.05 typically accounts for coating weight plus mill & weld tolerance. However, since other miscellaneous appurtenances (such as stops at each end) are present, a factor of 1.10 will be utilized.
- Hoist load factor (HLF): The hoisting of the load is performed manually; therefore, the hoist speed is relatively slow. A factor of 1.10 will be used in this example since the lift load is relatively low. A higher factor is justifiable for higher lift loads.
- The monorail system's classification is Class A since it is rarely in service.
- Allowable fatigue stress range from Table 3 is 63 ksi.
- Based on a F_y of 36 ksi and using Equation 8, C_c equals 126.1.
- Since Case 1 or Stress Level 1 is being investigated, then the constant N equals 1.10.

Loads

The uniform load (w) is the weight of the beam with the appropriate load factor. Therefore, $w = 1.10 \times 25.4 = 27.94$ lb/ft.

The point load (P) applied at the midspan of the beam is the lift load plus the trolley weight with appropriate load factors applied. Since all factors are 1.10, then $P = 1.10 \times (4000 + 250) = 4675$ lb.

Per AISC ASD, the axial load (P_{ax}) is 10% of the point load (P) and the lateral load (P_{lat}) is 20% of the point load (P). Therefore, $P_{ax} = 0.10 \times P = 467.50$ lb and P_{lat} is $0.20 \times P = 935$ lb.

Determine Axial Stress and Allowable

Since the beam area of the S10x25.4 is 7.46 in^2 , the actual axial stress (f_a) is $P_{ax}/7.46 = 0.06$ ksi.

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In order to determine the axial allowable, KL/r needs to be determined. KL/r for the major and minor axis is 32.43 and 138.37 respectively. The KL/r to use is the maximum of two values; hence, KL/r is 138.37. Since KL/r is greater than C_c , then Equation 9 is used to determine the axial allowable stress resulting in $F_a = 7.09$ ksi.

The interaction equation used to evaluate the combined stresses of the beam is based on the ratio of the actual axial stress to the allowable stress (f_a/F_a). Since this ratio is 0.009 and is less than 0.15, then only Equation 12 needs to be evaluated to determine the interaction ratio (or unity ratio).

Determine Bending and Torsional Moments

Bending about the major-axis of the beam is calculated for the uniform beam dead load with load factor applied and the point load applied at the midspan of the beam. Therefore, the major-axis bending moment (or in-plane bending) is

$$M_{ipb} = \frac{1}{8} wL^2 + \frac{1}{4} PL = 5.071 + 154.275 = 159.346 \text{ in} - \text{kips}$$

Bending about the minor-axis of the beam is determined using the lateral load applied at the midspan of the simply supported beam.

$$M_{opb} = \frac{1}{4} P_{Lat} L = 30.855 \text{ in} - \text{kips}$$

The torsional moment is determined by applying the lateral load at the bottom of the beam times one-half the beam depth.

$$M_{Tor} = P_{Lat} \frac{\text{Depth}}{2} = 4.675 \text{ in} - \text{kips}$$

Determine Bending Stresses

The bending stresses are determined using the bending moments divisible by the approximate section modulus of the beam (i.e., M/S). For an S10x25.4, $S_x = 24.7 \text{ in}^3$ and $S_y = 2.91 \text{ in}^3$. The stress caused by the torsional moment is additive to the minor axis bending stress and is calculated using the section modulus of the flange of the S-beam. With the properties of the flanges of the S-beam being 4.661 inches wide by 0.491 inches, the section modulus (S_{flg}) is determined to be $\frac{1}{6} bt^2 = 1.778 \text{ in}^3$.

Therefore, the bending stresses are

$$f_{bx} = \frac{M_{ipb}}{S_x} = 6.451 \text{ ksi}$$
$$f_{by} = \frac{M_{oipb}}{S_y} + \frac{M_{tor}}{S_{flg}} = 13.233 \text{ ksi}$$

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Bending Allowables

Based on Table 1, the bending allowable using Case 1 (Stress Level 1) is $0.60 \times F_y$ for both the major and minor axis of the S-beam.

$$F_{bx} = F_{by} = 0.60F_y = 21.60ksi$$

Interaction Equation

As previously mentioned, the unity ratio of the monorail beam is determined using Equation 12.

$$UR = \frac{f_a}{F_a} + \frac{f_{bx}}{F_{bx}} + \frac{f_{by}}{F_{by}} = 0.920$$

With the unity ratio being less than 1.00, the beam is capable of supporting the 2-ton required lift load. Deflection, fatigue, and local bending of the bottom flange must now be examined.

Local Bending of the Bottom Flange

Since this design check was not covered in detail in this course, the calculations will not be shown. Calculations were performed and the local bending stresses of the bottom flange were well within acceptable values for the specified design lift load.

Check Deflection

With a deflection allowable of $L/450$, the beam deflection can not exceed 0.293 inches. Using the deflection equations for a simply supported beam, the actual vertical deflection of the S10x25.4 beam with no load factors applied is

$$\Delta = \frac{5wL^4}{384EI_x} + \frac{PL^3}{48EI_x} = 0.059inches$$

where the first component is the deflection due to the beam's own weight and the second component is the lift load plus trolley weight located at the midspan of the beam. The value of the variables used are $w=25.4$ lb/ft, $L = 11$ feet, $E = 29000$ ksi, $I_x = 124$ in⁴, and $P = 4250$ lb (all units must be converted to pounds and inches prior to substitution). Since 0.059 inches < 0.293 inches, the beam deflection is adequate.

Check Fatigue

Fatigue is checked by finding the maximum stress range encountered by the beam and comparing it to the allowable range. The maximum stress range for this simply supported beam is calculated by taking the beam stress encountered during the lifting of the maximum load and subtracting the beam stress for the unloaded

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condition (i.e., stress caused by the beam's weight only). From the previous calculations, the maximum in-plane bending stress is 6.451 ksi (without subtracting the unloaded condition). As was initially determined, the allowable stresses range for this monorail is 63 ksi. Since 6.451 ksi is far less than the 63 ksi allowable, no further calculations are necessary as the monorail meets the fatigue criteria using this initial conservative check.

Important Points

The purpose of this course is to present a basic concept for the design of a single girder monorail system for bottom-running manually-driven trolley hoists. The concept and procedures were presented in a manner that it is useful for a general audience as well for civil or structural engineers performing such designs. At the end of this course, the reader should understand the following points:

- A properly designed monorail system requires adequate pre-planning.
- A monorail can increase productivity and safety while reducing costs and injury to personnel.
- An operational safety plan is an important element in a properly planned and designed monorail system.
- The monorail classification helps determine the maximum allowable stress range for use in fatigue checks.
- The design of a monorail requires consideration of various load types and combinations.

Disclaimer

The material presented in this course is intended only for general familiarization with the subject matter and for educational purposes. The course does not cover all aspects of the subject. Use of this material in any manner whatsoever shall only be done with competent professional assistance. The author provides no expressed or implied warranty that this material is suitable for any specific purpose or project and shall not be liable for any damages including but not limited to direct, indirect, incidental, punitive and consequential damages alleged from the use of this material.

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References

1. American Institute of Steel Construction (AISC), *Manual of Steel Construction, Allowable Stress Design*, 9th Edition.
2. American Institute of Steel Construction (AISC), *Manual of Steel Construction, Load and Resistance Factor Design*, 3rd Edition.
3. Crane Manufacturers Association of America, Inc. (CMAA) Specification No. 74, Revised 2000, *Specifications for Top Running and Under Running Single Girder Electric Overhead Cranes Utilizing Under Running Trolley Hoists*.
4. Material Handling Industry of America (MHIA) website (www.mhia.org).
5. Monorail Manufacturers Association, Inc (MMA) website (www.mhia.org/psc/PSC_Products_Monorail.cfm).
6. Gorbel, Inc. website (www.gorbel.com). Gorbel is a manufacturer of overhead material handling equipment. This author has no association with Gorbel, Inc.
7. Department of the Interior (DOI), Safety Management Information System website (<http://medical.smis.doi.gov>)
8. Hoist Manufacturers Institute (HMI) website (HMI's website is part of MHIA's website (see reference 4). "Shall's and Shall Not's for Hand Chain Manually Operated Chain Hoists". This document is for free download at website available in PDF format.
9. *Roark's Formula's for Stress and Strain*, 6th Edition, Chapter 7, Page 207; Raymond J. Roark & Warren C. Young; McGraw Hill Book Company, January 1989.
10. Steel Design Guide Series 9: Torsional Analysis of Structure Steel Members, American Institute of Steel Construction, Inc. (AISC), 1997.

Additional Resources

The references below are provided for the reader as additional sources for the design of monorails and other overhead material handling systems:

1. ASME/ANSI B30.2, "Overhead and Gantry Cranes (Top Running Bridge, Single or Multiple Girder, Top Running Trolley Hoist)."
2. ASME/ANSI B30.9, "Slings."
3. ASME/ANSI B30.10, "Hooks."
4. ASME/ANSI B30.11, "Monorails and Underhung Cranes."
5. ASME/ANSI B30.16, "Overhead Hoists (Underhung)."
6. ASME/ANSI B30.17, "Overhead and Gantry Cranes (Top Running Bridge, Single Girder, Underhung Hoist)."

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7. ASME/ANSI B30.20, "Below-the-Hook Lifting Devices."
8. ASME/ANSI B30.21, "Manually Lever Operated Hoists."
9. *Code of Federal Regulation*, Title 29, Part 1910.179, "Overhead and Gantry Cranes."
10. *Code of Federal Regulation*, Title 29, Part 1910.184, "Slings."
11. *Code of Federal Regulation*, Title 29, Part 1926.550, "Cranes and Derricks."
12. CMAA Specification No. 70, *Specifications for Electric Overhead Traveling Cranes*.
13. NFPA 70, Article 610, *Cranes and Hoists*.