Bracing System Design

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1.0 INTRODUCTION

Bracing systems serve a number of important roles in both straight and horizontally curved bridges. The braces provide stability to the primary girders as well as improving the lateral or torsional stiffness and strength of the bridge system both during construction and in service. Depending on the geometry of the bridge, braces may be designated as either primary or secondary members. In the AASHTO LRFD Specifications [1], the member designation as primary or secondary is typically assigned based upon whether the member has a design force obtained from a structural analysis. For example, a first-order analysis on a straight bridge during construction will often result in no forces in the cross frames and the braces are often designated as a secondary member. In many situations, the removal of the brace can result in a partial or complete collapse of the structure due to instabilities that can develop as a result of the larger unbraced length. In cases such as this, the engineer needs to recognize the importance of the brace and design the members accordingly. This course provides an overview of the design requirements of the braces so that engineers can properly size the members to ensure adequate strength and stiffness.

In general, this course discusses the design of bracing systems for the superstructures of straight and curved girder systems. I-girder and box shaped members are covered throughout this course. Bracing for other types of bridges, such as truss, arch or towers is not specifically addressed; however much of the information included in the course may be applicable.

The course has been divided into five primary sections. Following this introduction, an overview of bracing utilized for I-girders is covered. A discussion of the bracing systems for tub girders is then provided. The next section of the course outlines the design requirements for the members and connections of bracing systems. The final section contains simplified solutions for the calculation of geometric properties for tub girders.

Regardless of whether the bracing systems are utilized in straight or horizontally curved girders, a clear understanding of the torsional behavior of both I-shaped and tub girder sections is important. The need for torsional stiffness in horizontally curved girders is relatively obvious since the girders are subjected to large torques due to the geometry of the bridge. However, understanding the necessity of adequate torsional stiffness in straight girders is also important since lateral-torsional buckling often controls the design of the girders during construction. In many sections, such as tub girders, the presence of bracing dramatically impacts the torsional stiffness of the section. Lateral instability of flexural members always involves torsion of the cross section. Therefore, the remainder of this introductory section is focused on the torsional stiffness of open and closed cross sections as well as a discussion of the buckling behavior of steel bridge systems.

1.1 Torsional Behavior of Open and Closed Girders

Torsional moments are resisted by the shear stresses on the girder cross section. The torsional resistance in thin-walled structures is usually categorized as either Saint-Venant torsional stiffness or warping torsional resistance. The Saint-Venant stiffness is often referred to as uniform torsion since the stiffness does not vary along the length and is also not sensitive to the support conditions of the section. St. Venant torsion results in a pure shear deformation in the plane of the plates that make up the member.

The warping torsional resistance, on the other hand, is often referred to as non-uniform torsion since the stiffness is associated with the bending deformation in the plane of the individual plates. The warping stiffness of a section is related to the member's resistance to warping deformation. Two I-shaped sections subjected to a torque at the ends are shown in plan in Figure 1 to illustrate warping deformation and also warping stiffness. Figure 1a shows that warping deformation consists of a twist of the flanges relative to each other about a vertical axis through the web. Warping deformation distorts the cross section such that it no longer is a plane section because the two flanges have distorted relative to each other. Twist about the longitudinal axis of the member in Figure 1a is prevented at one end, however the warping deformations are not restrained. Since the section is free to warp along the entire length, the flanges remain straight as they twist relative to each other and the member only possesses St. Venant torsional stiffness.

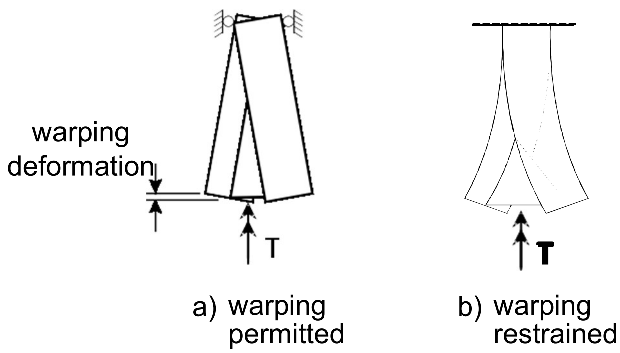

Figure 1 Warping Stiffness is Related to the Bending Stiffness of the Plate Elements.

The wide flange section in Figure 1b has both twist and warping deformation prevented at one end. With warping restrained at just one location along the length, the member cannot twist without bending the flanges. Since the flanges must bend if the member twists, the section therefore has warping stiffness. The warping torsion produces longitudinal stresses in the flanges of the member.

Many members do not have a physical restraint preventing warping as shown in Figure 1b, however the member still has warping stiffness if twist is prevented at a minimum of two points along the longitudinal axis. The twist restraint can come from sources such as cross frames that prevent the section from rotating about the longitudinal axis, but otherwise do not specifically restrain warping deformation of the section. Since the bending stiffness is very sensitive to the unsupported length, the warping stiffness is highly variable with the unbraced length.

In general, both Saint-Venant and warping torsional stiffness are developed when thin-walled members are twisted. The torsional moment resistance, T_T, of a section is a function of the uniform torsional (T_{UT}) and warping torsional (T_W) components as follows:

$$T_T = T_{UT} + T_W \tag{1}$$

The uniform torsional component can be expressed as follows:

$$T_{UT} = GJ\frac{d\phi}{dx} \quad (2)$$

where G is the shear modulus, J is the torsional constant, ϕ is the rotation of the cross section, and x denotes the longitudinal axis of the member. The torsional constant of an open section is given by the following expression:

$$J = \frac{1}{3}\sum_i b_i t_i^3 \quad (3)$$

where b_i and t_i are the respective width and thickness of the plate elements that make up the cross section of the girder. The torsional constant for single cell box or tub girders is given by

$$J = \frac{4A_0^2}{\sum_i b_i / t_i} \quad (4)$$

where A_0 is the enclosed area of the cross section of the box girder, and the variables b_i and t_i in the summation are the respective width and thickness of the *i*th plate that make up the cross section. For example, in a box or tub girder with a cross section made up of four plates, the denominator in Equation 4 is calculated by simply summing the width-to-thickness ratios of the four plate elements. A_0 is typically defined by the area enclosed from the mid-thickness of the plates that make up the cross section.

The warping torsional component can be expressed as follows:

$$T_W = EC_w \frac{d^3\phi}{dx^3} \quad (5)$$

where E is the modulus of elasticity, and C_w is the warping constant. For I-shaped sections bent in the plane of the web, the warping constant is given by the expression:

$$C_W = I_t h_o^2 \rho (1-\rho) \quad (6)$$

$$\rho = \frac{I_{yc}}{I_y} \quad (7)$$

where I_{yc} and I_y are the respective moments of inertia for the compression flange and the entire section about an axis through the web, and h_o is the spacing between flange centroids. For a doubly symmetric section, the value of ρ is 0.5 and Equation 6 reduces to the following expression:

$$C_w = \frac{I_y h_o^2}{4} \quad (8)$$

A rigorous theory for warping torsion was established by Vlasov [2]. The warping torsional stiffness often plays an important role in the total stiffness in girders with an open cross section such as I-shaped girders. For open sections with a relatively long length, the St. Venant stiffness dominates the total stiffness, while for shorter segments the warping torsional stiffness plays a much more significant component in the total stiffness. Closed box or tub girders are usually dominated by Saint-Venant torsion due to the closed cross section and the longitudinal normal stresses due to warping torsion are usually negligible [2]. The large Saint-Venant stiffness of a box or tub girder provides a torsional stiffness that may be 100~1000 times that of a comparable I-section.

The shear stress due to Saint-Venant torsion can be solved using Prandtl's membrane analogy [2]. For example, for girders with a single cell cross-section, a uniform shear flow, q, develops along the perimeter of the box and can be determined using the Bredt's equation:

$$q = \tau t = \frac{T_T}{2A_0} \tag{9}$$

in which t is the thickness of the plate, and τ is the shear stress, which is essentially uniform through the thickness of the plates. The distribution of torsional shear stress is demonstrated for a tub girder in Figure 2.

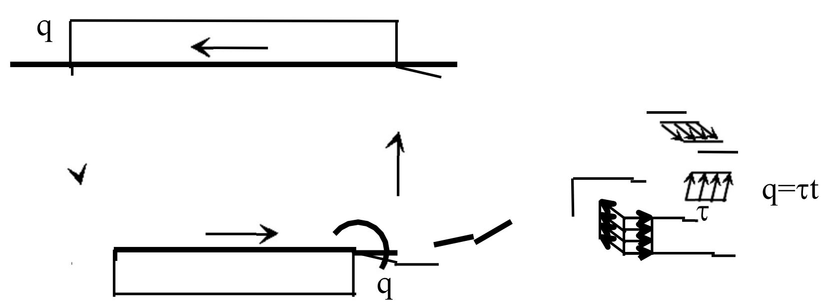

Figure 2 Shear Flow in Tub Girder Due to Saint-Venant Torsion

Although the torsional warping stresses in the box or tub girder are usually negligible, significant warping stresses due to the cross-sectional distortion of tub girders may develop, as is discussed later in this course. The large torsional stiffness of box or tub sections in bridges is the result of the closed cross section once the concrete deck cures. During construction of tub girders, the steel girder is an open section and requires bracing to be designed by the engineer that will stiffen the tub girder. The bracing systems for tub girders are covered later in the course.

1.2 Lateral Torsional Buckling

The overall stability of the girder system can be improved by either altering the geometry of the individual girders or by providing braces to reduce the unsupported length of the girders. Providing bracing is usually the more efficient solution and there are a variety of bracing systems that are provided as is discussed later in this course. The elastic buckling solution for doubly- symmetric beams is given in the following solution derived by Timoshenko [3]:

$$M_{cr} = \frac{\pi}{L_b}\sqrt{EI_yGJ + \left(\frac{\pi E}{L_b}\right)^2 I_yC_w} \tag{10}$$

where, L_b is the unbraced length, and the other terms are as defined above. The first term under the radical in Eq. 10 relates to the St. Venant torsional stiffness, while the second term within the radical reflects the warping stiffness of the beam. Equation 10 was derived for the case of uniform moment loading. Most design specifications make use of solutions derived for uniform moment and then use a moment gradient factor (C_b) applied to the uniform moment solution to account for the benefits of variable moment. In the derivation of the buckling expression, Timoshenko assumed that the ends of the sections were restrained from twist. Although restraint against lateral translation of the section was stated in the original derivation, the assumed support condition was never applied or required to derive the expression. Therefore, effective bracing of beams can be achieved by restraining twist of the section, which is the primary means of bracing I-shaped members in bridges with the use of cross frames or diaphragms. Twist of the section can also be restrained by preventing lateral translation of the compression flange of the section, which therefore introduces another means of bracing. Both lateral and torsional bracing requirements are discussed later in this course.

Lateral torsional buckling of closed box girders is not typically a concern due to the extremely large torsional stiffness of the closed cross section. During construction of tub girders a quasi-closed section is typically created by using bracing that simulates the stiffness of a top plate. Global buckling failures of tub girder sections have occurred during construction when proper bracing was not provided [4].

1.3 Categories of Bracing

Bracing systems that are used to increase the stability of structural systems can be divided into the four categories represented in Figure 3. This section introduces the basic bracing categories, which are covered in more detail in the remainder of this course. Although the focus of this document is on bracing for the super-structure elements of steel bridges, the basic categories also apply to columns and frames, which is demonstrated in Figure 3. Diagonal bracing such as that depicted in Figure 3a fits into the category of relative bracing since the braces control the relative movement of two adjacent points at different lengths along the main members. The lateral trusses that are used to create quasi-closed tub girders and the bottom flange bracing on I-girder systems to improve the lateral stiffness fit into the category of relative bracing. Another very common type of bracing in steel bridges are nodal systems such as those depicted in Figure 3b. Nodal braces control the deformation of a single point along the length of the member. Cross