Specification for Torsional Bracing Design of Steel I Girder Simple Span Bridges During Construction Stage

T N Huynh\textsuperscript{1,*}, R A Nguyen\textsuperscript{1}, D M Pham\textsuperscript{1}, T L T Pham\textsuperscript{1} and K T Nguyen\textsuperscript{1}

\textsuperscript{1}Viet Nam National University Ho Chi Minh City, University of Technology, Hochiminh, 72506, Vietnam.

Email: huynhngocthi@hcmut.edu.vn

Abstract. Nowadays, steel bridge structure is becoming the trend of highways and bridges construction industry on not only the material characteristic but also its ability to be manufactured easily and reduce the constructing time. However, this structure still has its own disadvantages. One of the most critical factors greatly influencing the performance of the whole structure is the buckling capacity of the main girders, especially during construction stage. The most common solution for increasing the structure’s buckling capacity is to provide it with discrete bracing along the girder’s length. The designing of bracing for steel bridges requires high precision. If the design of the system is much stiffer than it demands, the structure will easily be prone to fatigue problems. In the other hand, if the bracing design does not meet its required stiffness, the whole structure’s stability will greatly reduce. Presently, many projects are designed too sufficiently leading to a huge waste of cost and time. Therefore, the expected results of this study are to propose an optimal design process for the bracing system design of steel I girder simple span bridges and a finite element model of a real-life steel bridge to confirm the reliability of the specification proposed.

1. Introduction

One of the major limitations in the design of steel girder bridges in general and the simple supported steel bridge in particular is the lateral buckling of the main girder which is named the steel girder overall instability phenomenon. This phenomenon occurs mainly at the construction stage when the slab deck has been not rigid making the composition between the slab deck and main steel girder unfinished. The characteristic of overall stability is when the load reaches a specific value, beside deflection in bending plane, there is deformation outside the bending plane. The shape of girder section does not change but girder sections rotate relatively with each other. In this time, girder has to suffer both bending and torsion; girder axis deflects in bending plane, lateral buckling, warp out of the bending plane (Figure 1) and quickly loses bearing capacity [1].

This can be controlled by many methods. The most popular method is to add the intermediate bracing systems (IBS) along the working girder length. However, the next problem is how to design the IBS suitable for different steel bridge structures. In most reports of steel bridge failures, bridge collapse accidents usually occurs in the construction stage before the slab deck is rigid. Except for the problems of lifting the main girder in bridges with a horizontal curve, the majority of other incidents are related to the IBS [2]. The unsafely design of the IBS can easily lead to serious consequences in the construction stage due to lateral buckling by torsion happens rapidly and suddenly when the internal force in girder exceeds the ultimate value. When this happens, although figured out, it is very
difficult to intervene. Reversely, if the IBS are designed excessively, their specific stiffness will be larger than the required one then it is very costly in both material and installing process. This also leads to cracks in exploitation stage at connection locations of IBS due to vehicles repetition of live load causing local stress at these points. These problems make not only the higher cost in maintenance but also the unsafety of the IBS and bridge structure.

Although the role of IBS is very important in the steel bridge structure, until 2015 the US Federal Highway Administration and National Steel Bridge Alliance (FHWA and NSBA) have provided handbooks mentioning to the bracing system design and design example of this system in steel bridges [2]. However, these documents do not point out the way to design IBS for simple supported steel bridge and the IBS design process for this type of bridge also has not been established to serve the design work for engineers.

Therefore, this study aims to give out an IBS design process which is as optimal as possible for simply supported steel bridge. Moreover, the behavior of IBS will be analyzed in both construction and exploitation stages to assess their working capacity to ensure requirements such as reducing the cost of materials in bracing system design, stability of bridge structure during construction stage and no damage of bracing system in exploitation stage. In addition, the rationality of the proposed process will be validated by comparing the critical moment value determined from the process and from the finite element method. Finally, targets of this process as well as this study is to ensure three tasks: 1) The bridge structure is overall stable in construction stage with the optimum structural number; 2) The IBS is not destroyed in both construction and exploitation stage; and 3) The ability of the material is taken advantage thoroughly aiming to tend the purpose of economic and optimal design.

2. Methodology
2.1 Scope of the study and assumption
The design philosophy will be based entirely on the AASHTO specification and the LRFD method. According to the objectives of the study, the I Strength and I Service limit state without wind load will be the two main states used in this process.
In order to simplify the design process, some assumptions are proposed as follows:
1. Wind load does not force on the bridge structure and only dead load, construction and vehicle live load are taken in account. With these types of loads and the limited states used, authors assume that just vertical load acts on the bridge structure.
2. The theory of stiffness of bracing system for twin-girder structure will be applied for multi-girder bridge structure. This assumption will be confirmed in the evaluation of analysis results.

2.2 Theoretical basis
Effective IBS require suitable stiffness and bearing capacity [3]

2.2.1 Stiffness of bracing system
Anti-lateral buckling capacity caused by torsion of steel girder is defined by the ultimate moment value $M_{cr}$ of girder. When internal force in girder exceeds the ultimate moment value, overall instability phenomenon happens. Ultimate moment value of steel girder is calculated by equation.

$$M_{cr} = \left( C_{bu}^2 M_0^2 + \frac{n C_{h}^2 \beta_1 E I_{eff}}{C_I L} \right)^{1/2}$$

(1)

In this research, the cases that the IBS are uniformly distributed are considered. Spacing among IBS, $L_b$ is chosen from the ultimate internal moment value $M_0$ can be calculated by following:

$$M_0 = \pi E \left( I_{yc} / L_b \right) \left[ 2G \left( J / L_{yc} \right) + \pi^2 \left( d / L_b \right)^2 \right]^{3/2}$$

(2)
From the chosen value $L_b$, the minimum number of IBS ($n$) can be determined. Minimum overall stiffness of IBS can be calculated reversely from formula (1) after $M_{cr}$ is substitute by $M_u$.

In safety aspect, the ultimate internal moment value in Eq. (1) of main girder without IBS has been proposed to omitted [3] since it is quite small compare to the ultimate moment value of the system when there is IBS and for easier calculation. So that, from Eq. (1), value of overall stiffness $\beta_T$ is as following:

$$\beta_T = \frac{1.2L M_u^2}{C_{ls}^2 n E I_y}$$

(3)

This overall stiffness value illustrates the composite work of the entire of the structure system including main girder and IBS. Specifically, this composition shown by equation:

$$\frac{1}{\beta_T} = \frac{1}{\beta_b} + \frac{1}{\beta_g} + \frac{1}{\beta_{sec}}$$

(4)

where:

$\beta_b$: specific stiffness of IBS. According to the assumption, specific stiffness of twin-girder system is applied (Figure 2). Errors by using specific stiffness of other type of structure will be discussed later.

$\beta_g$: stiffness in bending plane of main girder is calculated by:

$$\beta_g = \frac{24(n_y - 1)}{S E I_y} \frac{S^2 E I_y}{n_y L^3}$$

(5)

$\beta_{sec}$: stiffness of girder cross section is calculated:

$$\beta_{sec} = \frac{3.3E}{h_o} \left( \frac{1.5h_o b_t^3}{12} + \frac{t b_t^3}{12} \right)$$

(6)
After $\beta_T$, $\beta_g$ and $\beta_{sec}$ are determined from Eq. (3), Eq. (5) and Eq. (6) respectively, $\beta_b$ will be obtained from Eq. (4). With the value of $\beta_b$, the height of IBS and section of each component in them can be preliminary determined from equations in Figure 2.

### 2.2.2 Bearing capacity

Moment value of the IBS when they are active linear proportional to the initial error skew angle at joint point. Conclusion above is applied to determine the rotation angle at the joint, $\phi_t$, as well as the moment value in IBS [1].

\[
\phi_t = \frac{\phi_b}{1 - \frac{\beta_T M}{\beta_t M_{cr}}} \\
M_{bt} = \beta_T (\phi_t - \phi_b)
\]

From equation (7), it is concluded that if the stiffness is designed to equal to the minimum overall stiffness of girder determined in Eq.(1) and the moment value in girder reaches the ultimate one, deflection angle will reach an infinite leading to moment in IBS extremely large. Therefore, the design overall stiffness of the IBS is proposed to equal to two times larger than the minimum stiffness [1]. With above proposal, the design overall stiffness can be calculated by:

\[
\beta_T = \frac{2.4LM^2}{\phi n C L E I_{eff}}
\]

When IBS work with main girders together, the initial error skew angle can be assumed equal to $L_b/(500d)$ radians with $L_b$ is the spacing among IBS and $d$ is the girder height. Moment value of IBS in working phase is equal to:

\[
M_{br} = \frac{0.024LM_u}{n C_{bb} L_b}
\]

From value of $M_{br}$ determined by Eq.(10), the stress of each component in IBS can be obtained by formula in Fig. 2 (Please refer [1] for understand more detail from Eq. (1) to Eq. (10))

### 2.3 Theoretical basis for finite element method (FEM)

To analyze the stability of the bridge structure without IBS, the finite element method is used as a theoretical basis [4]. Set $\lambda_{cr}$ as critical load factor. The static equilibrium equation of a structure at a deformed state is expressed as:

\[
[K][U] + [K_G][U] = [P]
\]

where $[K]$: elastic stiffness matrix, $[K_G]$: geometric stiffness matrix, $[U]$: displacement of structure and $[P]$: applied load.

From Eq. (11) the equilibrium equation is rewritten as:

\[
[K + \lambda K_G][U] = [P]
\]

Set the equation $[K + \lambda K_G] = [K_{eq}]$: Equivalent stiffness matrix.

In order for a structure to become unstable, the Eq. (12) must have a singularity. That is, buckling occurs when the equivalent stiffness matrix becomes zero.

- $|[K_{eq}]| < 0$ ($\lambda > \lambda_{cr}$) Unstable equilibrium state
- $|[K_{eq}]| = 0$ ($\lambda = \lambda_{cr}$) Unstable state
- $|[K_{eq}]| > 0$ ($\lambda < \lambda_{cr}$) Stable state

Therefore, the instability analysis problem in Eq. (12) can be contracted to an eigenvalue analysis problem.

\[
[K + \lambda K_G] = 0
\]
where $\lambda$: eigenvalue (critical load factor). The critical load equals the applied load multiplied by the critical load factor [4] rewriting as the following formula: $\{P_{cr}\} = \lambda_{cr} \{P\}$ (where $\{P_{cr}\}$: critical load vector, $\{P\}$: applied load vector). Hence, with the known applied load $\{P\}$, in case $\lambda_{cr} > 1$, $\{P\}$ is less than the critical load $\{P_{cr}\}$ or in other words, $\{P\}$ has not reached the critical value. This time the system is stable. Case $\lambda_{cr} < 1$ or $\lambda_{cr} = 1$, $\{P\}$ has reached or exceeded the $\{P_{cr}\}$. Therefore, the ultimate moment $M_{cr}$ is easily determined from the moment due to the loads in the construction stage and the critical factor $\lambda_{cr}$ obtained from simulation program (FEM).

3. Analysis cases

3.1 Analysis object

In this study, the Luong Thuc Bridge (Ca Mau Province) has been selected as the research object [5]. Luong Thuc Bridge has a structure of traditional girder system, with horizontal bracing system of I-shaped steel beams. The bridge has a total length of 90m, including 3 spans, maximum span length is 35.4m, with a beam length of 35.9 m. The bridge width is 6m and the distance between the closest two main beams is 1.5m. Horizontal beams at the bearings are 0.6m high and the intermediate bracing system uses horizontal I-shaped 400 steel beams.

3.2 Numerical model of the steel bridge with design IBS

To evaluate objectively the reliability of the proposed process, IBS of Luong Thuc bridge will be substituted by 4 different IBS in Figure 2 (except the last one). The cross-section size of each structure component and the height of the bracing system obtained from the proposed design process will be applied in these simulations. Bridge structure for each IBS will be analyzed in both working stages of bridge. Analysis result from the construction stage is used to evaluate the critical moment determined from the proposed process. The one from the exploitation stage will be applied to check the bearing capacity of each structure component in each type IBS. Input data based on the real model with simply supported I girder is suitable for AASHTO specification [6]. Besides, the main girder, cross girder and steel plate are simulated by plate element with 4 nodes for assessing the overall performance of components in a structural system. The structure component of IBS is modelled by beam element and the slab deck in exploitation stage is modelled by solid element.

3.3 Design loading

The strength I limit state and the service I are used to assess the stability and the displacement of the bridge structure, respectively [6]. Therefore, the load acting on the bridge in the construction stage includes dead load-self weight of all components in the structure and the construction live load (CLL). In addition, the live load – HL 93 is applied during the extraction stage.

3.3.1 Design process for bracing system

The design process is shown in Figure 3. The conditions for performing the loop are ensure the conditions as following
1. Stable in the construction stage,
2. Undamaged during both construction and exploitation stage, and
3. Economical and optimal design.

4. Results and discussion

4.1 Evaluation of the reliability of the design process

The results from FEM model are the ultimate factor $\lambda_{cr}$ (larger than 1 in all four types of IBS) and the internal stresses in the girder. From internal stresses at the top or bottom of the girder and the ultimate factor $\lambda_{cr}$, the ultimate moment value $M_{cr}$ of the girder in the FEM method can be easily obtained. At the end of the design process, the parameters of the IBS are determined. Thus, $M_{cr}$ of the proposed process is calculated for the purpose of evaluation and comparison. Table 1 shows the ultimate moment value obtained from FEM and proposed process. In this study, $M_{cr}$ from FEM is considered
Figure 3 Flowchart describing the IBS design process
the reliable result and used as the base to evaluate the accuracy of the proposed design process. Table 1 indicates that the maximum error is just 5.13%. In engineering, this error is acceptable. This negligible error indicates that the proposed design process is reasonable and optimal. Arising error is concluded due to the second assumption (refer section 2.1). Three of the four types of IBS designed show that the $M_{cr}$ value from FEM is larger than that in the proposed process, which proves that the individual stiffness of IBS in the multi-girder system is greater than that of the twin-girder system. However, taking account the individual stiffness of IBS in the multi-girder system is unnecessary and complicated. That, $M_{cr}$ defined from process is smaller than the reliable one from FEM, shows the safety of the process. Since then, the second assumption is completely reasonable and applicable for this design process.

4.2 Evaluation of the bearing capacity of the types of IBS in the exploitation stage.

Figure 4 and Figure 5 respectively show the maximum total displacement of the main girder and the maximum total stress in each component of IBS. These values of all four structural types of IBS are smaller than the allowable value. In addition, the smallest displacement value of the four structural types of IBS is about 82.22% of the allowed deflection one. Whereas, the smallest stress value of the ones is greater than 97% of the permissible one.

Table 1. The result of the ultimate moment value from the two methods

| Structural types | Simulated $M_u$ (kNm) | Calculated $M_u$ (kNm) | Percentage error (%) |
|------------------|-----------------------|------------------------|----------------------|
| I                | 3469                  | 3598                   | 3.72                 |
| K                | 3779                  | 3587                   | 5.09                 |
| X                | 3769                  | 3646                   | 3.26                 |
| Z                | 3778                  | 3584                   | 5.13                 |

Figure 4 Maximum value of total displacement of girder in both working stages

Figure 5 Maximum value of total stress in each component of IBS in in both working stages

These prove that:

1. The general working of bracing systems, main girder and deck slab is effective. In particular, the role and contribution to the overall stiffness of the bridge structure of the bracing systems and the hardening of the deck slab are very important and significant.
2. The limits of material and bridge structures are taken full advantage. In other words, IBS are designed economically and optimally.

5. Conclusion
To verify the applicability of the proposed process for designing IBS, the finite element method is used to determine the critical moment values in the construction stage, the total displacement in the main girder and the total stress in each component of IBS. As a result, the followings can be concluded:
1. Products including cross section area of each IBS component and height of IBS of the process are reasonable and optimal.
2. The proposed design process has ensured the two initial requirements: stability during construction stage and no damage in both working stages of the bridge structure.
3. The stiffness of the bracing system in the twin-girder system can completely be applied to design it in multi-girder system. This demonstrates that the stiffness of bracing system in multiple girder bridge structures does not change so much when the number of girder is greater than 2.
4. The proposed design process is reasonable, optimal and completely can be applied in reality.

References
[1] Todd A. Helwig, Liqun Wang, Cross-frame and diaphragm behavior for steel bridges with skewed supports, Research performed in cooperation with the Texas Department of Transportation and the U.S. Department of Transportation, Federal Highway Administration, 2003
[2] Todd Helwig, Joseph A. Yura, Steel Bridge Design Handbook: Bracing System Design, U.S. Department of Transportation Publication No. FHWA-HIF-16-002 - Vol. 13, December 2015
[3] Joseph A. Yura, Fundamentals of Beam Bracing, Engineering Journal, American Institute of Steel Construction, First quarter, p.11-26, 2001
[4] Analysis Reference of Midas Civil software, MIDAS Information Technology Co., Ltd. Profile of Luong Thuc Bridge, 3E Steel Co., Ltd.
[5] AASHTO. LRFD Bridge Design Specifications, 7 Edition. Washington D.C.: American Association of State Highway and Transportation Officials, 2014