Proceedings of the
Annual Stability Conference
Structural Stability Research Council
St. Louis, Missouri, April 2-5, 2019

Topology optimization of top lateral bracing for steel tub girder systems using genetic algorithm

Liwei Han[1], Yang Wang[2]

Abstract
The use of Steel trapezoidal box girder systems has gained increasing popularity in bridge applications as they feature high torsional stiffness and are aesthetically appealing. However, during the concrete deck pour, the top flanges are in compression and the entire girder is susceptible to the failure mode of global lateral torsional buckling (LTB). Several incidents have occurred ranging from the excessive deformation to the complete bridge collapse. Usually a lateral truss system is installed at the top flange level to form a "pseudo-closed" section and to help resist LTB before concrete hardens. However, the installation of top lateral bracing along the entire girder span, albeit common in current practices, might not be efficient given the differential girder shear deformation distribution along the length. This paper presents a general approach for the topology optimization of the top lateral bracing configuration for the steel tub girder system. The optimization is formulated based on a modified genetic algorithm (GA) in conjunction of the 3D finite-element analysis implemented in Python-ANSYS APDL AAS coupling programming environment. The truss member number and connectivity are encoded in real-valued chromosomes and the objective function of the optimization is to minimize the total weight of the top lateral bracing system subjected to buckling constraints using the penalty function. Case studies are carried out and the optimized bracing configurations are compared with those from the previously-published studies. The results show that the proposed approach allows successful optimization of partial top lateral bracing system with improved efficiency and buckling resistance. The approach can also be used for the optimization of the lateral bracing of other long and slender girder systems.

1. Introduction
The steel trapezoidal box girder system, also known as steel tub girder system, has gained increasing popularity in bridge applications as they feature high torsional stiffness and are aesthetically appealing. However, inappropriately designed steel box girder system might be subjected to global lateral-torsional buckling (GLTB), a recently identified failure mode analogous to the lateral-torsional buckling (LTB) of a single beam occurring between intermediate bracing since the box girder could be long and slender as a whole structural unit.

[1] Senior Engineer, CHI Consulting Engineers, < lhan@chiengineers.com>
[2] Graduate Research Assistant, The University of Texas at Austin, < yangwang.structure@utexas.edu>

The most critical construction stage for a box girder system being prone to global lateral-torsional buckling is the deck placement when the dead load of the wet concrete is applied on the non-composite section while the deck is not able to provide effective bracing to the top flange before the concrete cures (Yura et al. 2008). Increasing attention has been drawn upon this failure mode in recent years since the structural failure of Marcy Pedestrian Bridge during the deck pour. It also occurred at multiple occasions that the bridges were experiencing excessive lateral-torsional deformations during erection, a sign of the load on structure reaching its critical buckling resistance (Han and Helwig 2016; 2017). However, unlike the lateral-torsional buckling of a single girder, global lateral-torsional buckling of the box girder or I-girder systems cannot be prevented by reducing the spacing between the intermediate bracing. Usually a lateral truss system is installed at the top flange level to form a "pseudo-closed" section and to help resist the lateral-torsional buckling before concrete hardens. However, the installation of top lateral bracing along the entire girder span, albeit common in current practices, is expensive and inefficient given the differential girder shear deformation distribution along the length and a previous study (Yura and Widianto 2005) recommends that top lateral bracing might only be needed near the end supports of the box girder or I-girder system, where the differential shear deformation is the largest.

This paper documents a computational study consisting of 1) development of an optimization procedure formulated based on a modified genetic algorithm (GA) in conjunction of the 3D finite-element analysis; and 2) finding the optimal steel diagonal truss configurations for the partial top lateral bracing system and compare them with the recommended ones from previous study.

2. Problem Statement

In this study, a steel trapezoidal box girder system was analyzed with objective to optimize the configuration of the partial top lateral bracing system. The optimal solution is defined as 1) the top diagonal truss configuration with the minimum weight satisfying the required buckling capacity.

Figure 1 depicts the model of the steel box girder with a partial top lateral bracing system and its buckled shape. The geometric parameters of the box girder section considered in study is detailed in Figure 2. The bridge girder has a total span length of 120 ft and is simply supported at two ends. A uniformly distributed load was applied along the centerline of the two top flanges. The details of the top lateral bracing and its parameterization in the simulation will be discussed in a latter section of this paper.

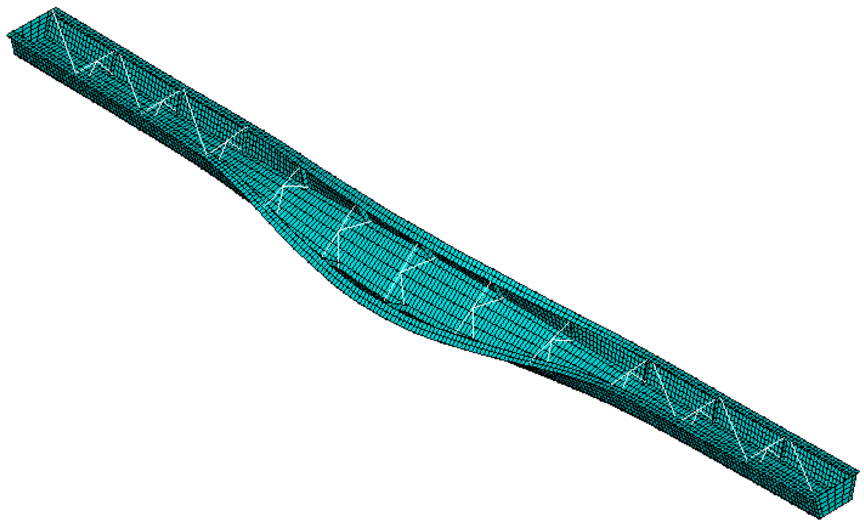

Figure 1. FE model of the buckled box girder

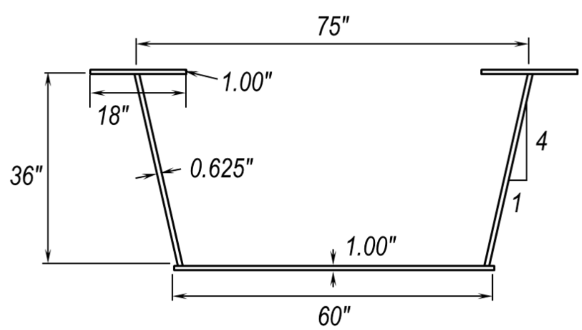

Figure 2. Geometric Parameters of the Box Girder Section

3. Genetic Algorithm Optimization

Figure 3 contains a chart illustrating the optimization procedure used in this study, which is based on a modified genetic algorithm (GA) in conjunction of the 3D finite-element analysis. Genetic Algorithm is a stochastic optimization technique, imitating Darwin's theory on natural evolution. Each potential solution to a problem is parameterized to a bit sequence or real-valued vector known as genotype or chromosome. The algorithm starts with initial population consisting of a pool of randomly created genotypes. In each iteration step (also known as generation) of the computation, the genotypes change by mutation and recombination (crossover). These genotypes will be evaluated and selected by their "fitness". This process is repeated until a termination condition is met. Genetic algorithm is effective in searching global optimum thus suitable to solving problems that are highly nonlinear and have large number of local minima, where gradient-based methods might be easily entrapped. This makes genetic algorithm an ideal candidate for this study since a large number of local minima might exist when bracing layout is variable (Balogh and Vigh 2012).

This optimization procedure was numerically implemented by Python-ANSYS APDL mixed programming. While the genetic algorithm was developed in Python, we took advantage of OmniORBpy, a free Python library that allows us to call ANSYS MAPDL in AAS server mode to perform linear elastic eigenvalue buckling analysis. The Calculated buckling load value will be returned to Python environment for fitness evaluation.

For the finite element analysis in ANSYS (2015), 3D 8-node shell element (SHELL281) was used for modeling web and flange plates and 3D 3-node beam element(BEAM189) are used for modeling top lateral bracing and intermediate K-type frames. Both elements feature quadratic displacement shape functions that capture the behavior of bending-dominant thin-wall structures with proved accuracy. (Helwig 1994; Quadrato 2010; Battistini et al. 2016).

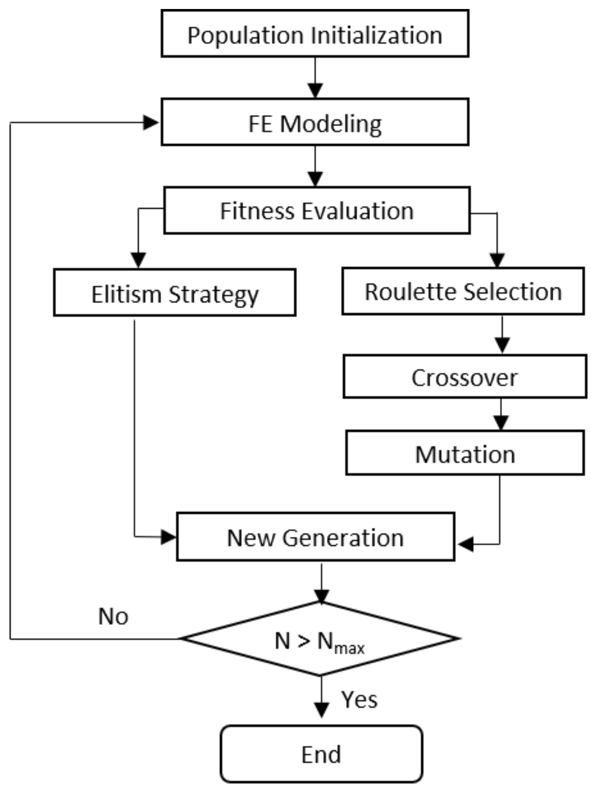

Figure 3. Flowchart of Optimization Procedure

3.1 Encoding Scheme

The box girder structure spans 120 ft, with 12 truss panels equally spaced at 10 ft apart. 11 K-type frames were placed at these panel points. WT 6×20 steel section was used for lateral truss and L 3×3×3/8 section was used for internal K-type frames. As illustrated in Figure 4, the lateral truss within a panel can be parameterized into integers ranging within [0,3] according to their truss connectivity patterns: D = 0 for absence of truss; D= 1, 2 for single diagonals; and D = 3 for cross diagonals. Therefore, the design space can be encoded to into a genotype vector containing 12 elements of integer value:

$$x = [D_1, D_2, D_3, \ldots, D_n] \tag{1}$$

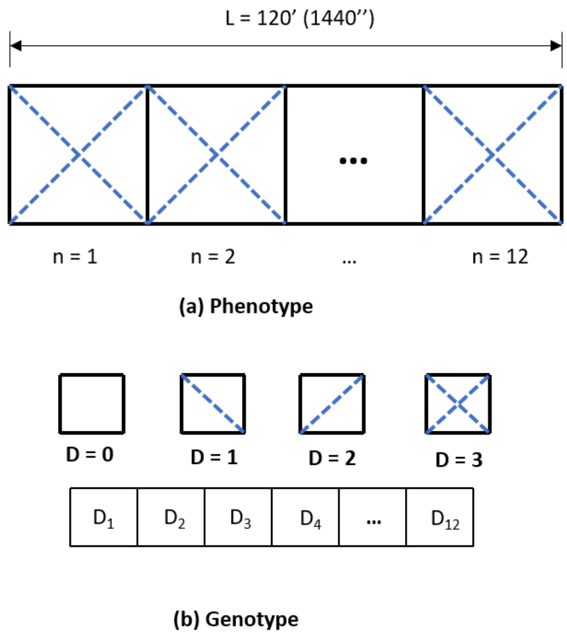

Figure 4. Encoding of the Top Lateral Bracing System

The population size considered for this study was limited to 40 to keep the algorithm efficient considering the large computational demand of 3D finite element analysis. An elitism strategy was adopted in this algorithm to preserve the best two (2) individuals, which can survive a generation cycle with immunity to the process of selection, crossover, and mutation. For the rest of the population, a Roulette wheel selection was performed based on a probability proportional to their Scaled Fitness Values (SFV):

$$SFV = \frac{1/R_i}{\sum 1/R_i} \tag{2}$$

where R_i is the rank of an individual genotype. As illustrated in Figure 5(a), each generation, two offspring genotypes were created from two parent genotypes by a uniform crossover operator with a probability of 50% for each individual gene. Because the genotype is a real-valued vector, a uniform mutation operator was used, subjecting each gene to mutation with a probability of 5%. The old gene will be replaced with a randomly generated integer ranging from 0 to 3 with uniform distribution as shown in Figure 5(b).

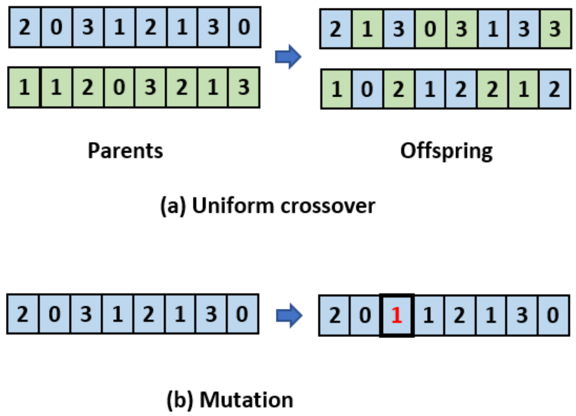

Figure 5. Crossover and Mutation

3.2 Fitness Function

The objective of the optimization is to minimize the fitness function typically used for genetic algorithm. Every generation, the buckling capacity of each individual structure in the pool was obtained from the eigenvalue buckling analysis in the FE program. The fitness of the individual was then calculated by the total mass of all top lateral bracing and was subject to buckling capacity constraint implemented by a penalty term P that augments the fitness function. The minimum required buckling capacity of the structure w_{cr} was set to be 500 lb/in. (6 k/ft.) for this study and the fitness function will be penalized by an increase of a large number for any constraint violation.

$$\min f(x) = k_1 \sum A_i l_i + P \quad \text{with} \tag{3}$$

$$P = 1000 \qquad \text{if } w < w_{cr} \tag{4}$$

$$P = (-0.5)^{w}/w_{cr} \qquad \text{if } w \geq w_{cr}$$

where w (lb/in.) is the uniformly distributed load applied on the structure determined from the eigenvalue buckling analysis, w_{cr} (500 lb/in.) is the minimum buckling capacity required, $k_1 = (1/A_{avg}l_{avg})$, A_{avg}, l_{avg} are the average sectional area and length of the top lateral truss diagonals, respectively.

4. Results and Discussion

The evolution of the fitness number for the best individual over each generation is presented in Figure 6, indicating the calculation had converged after approximately 40 generations before it reached the maximum iteration number. The top lateral bracing configuration of the best surviving individual is depicted in Figure 7(a) and the buckling capacity of this structure is 596.7 lb/in. (7.16 k/ft.). Meanwhile, given the additional constraint of bracing truss number being four (4), the most effective top lateral bracing configuration obtained from the optimization is depicted in Figure 7(b).

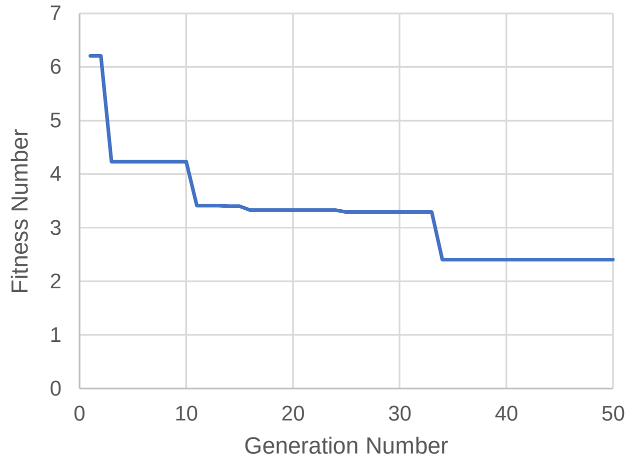

Figure 6. Convergence of the Algorithm

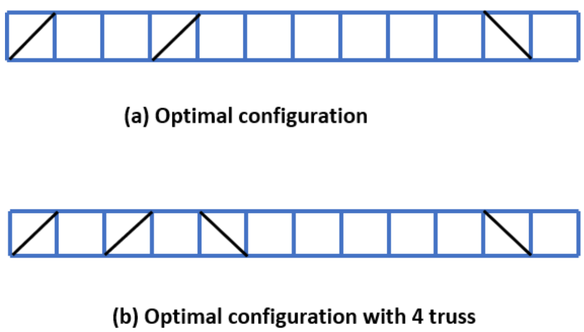

Figure 7. Optimal Top Lateral Bracing Configurations

The optimal top lateral bracing configurations shown in Figure 8 are inconsistent with previous study (Yura and Widianto 2005) on partially braced top flange diagonal systems, which asserts that the top lateral diagonals should be placed at the girder ends (e.g. Case A in Figure 8) where the differential shear deformation is the largest to achieve the most effective restraints against the global lateral-torsional buckling. A comparison of the buckling capacity between four (4) different 4-diagonal configurations were made for verification. While it is true that placing top lateral diagonals at the two ends (Case A) provides much greater restraints against global lateral-torsional instability than placing them at the mid-span (Case B) where differential deformation is insignificant. Case C and Case D (optimal individual obtained from optimization) are nevertheless more effective than Case A. In the latter two cases, single diagonal trusses were also placed near two ends, but their presence are discontinuous in adjacent panels.

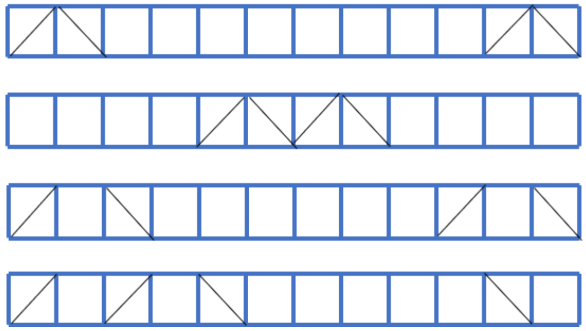

Figure 8. Comparison of the Buckling Load for 4-diagonal Configurations

5. Conclusions

Paper discusses the development of an optimization procedure formulated based on a modified genetic algorithm (GA) in conjunction of the 3D finite-element analysis to optimize the configuration of the partial top lateral bracing system of a steel trapezoidal box girder subject to the constraint of global lateral-torsional buckling. The proposed approach obtained optimal configurations with proved numerical stability. The best individuals found by genetic algorithm features a pattern that single steel diagonals are located near the girder ends with discontinuous presence in adjacent panels. This configuration was found to more effective in providing restraint against global lateral-torsional instability than the recommended configuration from the previous study, which recommends diagonals should be installed at end ends without discontinuity in adjacent panels. Further research is required to understand why the optimal configuration found by this study departs from previous knowledge that the steel diagonal trusses achieve the best efficiency at end panels where the transverse deformation is the largest.

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