Redundancy Analysis of Unbraced Network Arch Bridges

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ABSTRACT: The redundancy of a structural system is its ability to support loads even after a failure of one or several structural components. Redundancy analysis is vital to assess the safety and reliability of network arch bridges, particularly in the context of extreme events such as hanger replacement and hanger loss. Even though the Post-Tension Institute (PTI) offers specific design guidelines on handling abrupt cable loss and replacement for cable-stayed bridges, it failed to address the issue of gradual collapse comprehensively. However, comparable guidelines are lacking in the AASHTO design practices. While system factors for simple bridge systems have been extensively investigated, there is a lack of research on corresponding system factors for complex structures such as network arch bridges. Recently, an attempt was made to establish a step-by-step procedure to compute the system factors for a steel box tied arch bridge structure system. However, no studies were found to determine the system factors for freestanding network arch bridges. The lack of research or documentation outlining a specific methodology to establish the system factors for unbraced network arch bridges underscores the need for further research to establish design standards that prioritize the safety and resilience extreme circumstances. To address this knowledge gap, a parametric investigation is currently being conducted to develop deterministic and probabilistic procedures to determine the system factors for straight and moderately skew (skew < 20°) unbraced network arch bridges using finite element analysis (FEA). A 80.7 m (265 ft) long, 27.3 m (96.5 ft) wide, and 18° skew unbraced network arch bridge constructed in Detroit, Michigan, was used as the prototype and evaluated its performance during the hanger replacement scenario under dead load conditions. The results of the analysis indicate that the sequential replacement of hangers in a straight and moderately skew unbraced network arch bridges can be performed under its own weight without impacting the structural integrity.

1. INTRODUCTION

The network arch bridge concept was first developed by a Norwegian engineer Per Tveit in the late 1950s. Since then, several bridges have been built all over the world. A typical network arch bridge consists of two arch elements and a network of intersecting hangers, emulating a truss. A majority of bridges built in the world included transverse/portal bracing between the arches, and called tied network arch bridges. However, several straight bridges with unbraced arches were constructed in Europe and USA. In addition, a unique 18° skew bridge with unbraced arches is being constructed to carry the 2nd Avenue traffic over the interstate (I) 94 in Detroit, Michigan, USA.

As described in Mato et al. (2011), vertical loading on the deck is transferred to the arches through the hangers. As a result, the arches and tie girders become compression and tension members, respectively. Only the vertical reactions are transmitted to the foundations (Per Tveit 2009, Mato et al. 2011).

The behavior of a network arch is analogous to a simply supported beam. The arch would be the compression zone, the hangers would be the web, and the tie girder would be the tension zone. Hence, most of the vertical shear forces are resisted by the vertical components of the compressive force in the arch and some by the hangers. Bending moments are small in all elements (Per Tveit 2009).

Redundancy analysis is vital to assess the safety and reliability of network arch bridges, particularly in the context of extreme events such as hanger replacement and hanger loss. The American Association of State Highway and Transportation Officials (AASHTO 2020) refers to redundancy as the ability to support loads even after a failure of one or several structural components. Three types of redundancies could exist in a bridge: load path, structural, and internal redundancy.

Load path redundancy refers to the presence of multiple load paths in a bridge structure that can support the applied loads. This can be achieved by having multiple beams or girders, redundant members, and alternate load paths. However, this requires sufficient capacity on the alternate load paths to carry the load redistributed from the adjacent failed members (Fu and Wang 2015).

Structural redundancy denotes that the failure of a member only alters the boundary or support conditions without causing the entire superstructure to collapse. This means that the failure of a member does not result in a catastrophic failure of the entire structure (Fu and Wang 2015).

Internal redundancy refers to a structural member having an alternative and adequate load paths within the member itself (Fu and Wang 2015).

Hangers in network arch bridges help distribute the weight of the bridge deck evenly across the arch rib. If multiple hangers fail, it could lead to the redistribution of the load to the remaining hangers, arches, and the tie girders.

The Post-Tension Institute (PTI) offers specific design guidelines on handling abrupt cable loss and replacement for cable-stayed bridges. These recommendations are outlined in the Recommendation for Stay Cable Design, Testing, and Installation manual (PTI 2018). However, comparable guidelines are lacking in the AASHTO design practices (AASHTO 2017). While the PTI Recommendations offer some guidance on the analytical approaches using both quasi-static and dynamic scenarios in the commentary section, they provide insufficient advice on designing the global structural system. Additionally, there are no established general design standards for cable-supported bridges to withstand catastrophic events, such as abrupt cable loss, and the PTI Recommendations fail to address the issue of gradual collapse comprehensively. This underscores the need for further research to establish design standards that prioritize the safety and resilience of cable-supported bridges under extreme circumstances.

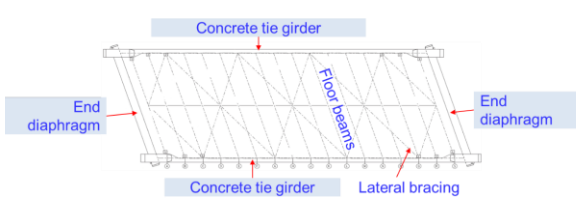
Although design guidelines exist for handling sudden cable loss and replacement in cable-stayed bridges, no such recommendations have been established for network arch bridges. This emphasizes the need for further research to develop analysis and design guidelines to handle extreme load cases.

Under the National Cooperative Highway Research Program (NCHRP) Report 406, Ghosn and Moses (1998) developed a sequential approach to assess the redundancy of the superstructure of simple bridge systems. The factor tables presented in this report were subsequently simplified and adopted in the AASHTO Manual for Bridge Evaluation (MBE) (AASHTO 2018). While system factors for simple bridge systems have been extensively investigated, there is a lack of research on corresponding system factors for complex structures such as network arch bridges. Zoli and Woodward (2005) made an effort to evaluate the performance of a 268 m (880 ft) long tied arch network bridge in response to cable loss. Additionally, Zheng et al. (2018) utilized the step-by-step approach developed in the NCHRP report 406 to compute system factors for a steel box tied-arch bridge structure system.

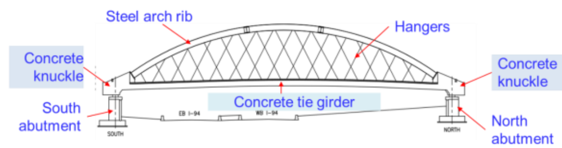
Further, there is a lack of research or documentation outlining a specific methodology to establish the system factors for unbraced network arch bridges. To address this knowledge gap, a parametric investigation is currently being conducted to develop deterministic and probabilistic procedures for determining the system factors for straight and moderately skew (skew < 20°) unbraced network arch bridges using finite element analysis (FEA). As an initiation, redundancy of an unbraced network arch bridge during hanger replacement, which is a planned activity, was considered for the analysis. The first step of this study focuses on evaluating the hanger replacement scenario under dead load conditions and this document presents the preliminary results of this analysis.

2. FINITE ELEMENT ANALYSIS

The 80.7 m (265 ft) long, 27.3 m (96.5 ft) wide, and 18° skew unbraced network arch bridge that is being constructed in Detroit, Michigan, was used as the prototype. Figure 1 shows the plan and elevation views of the bridge. Figure 2 shows the bridge cross-section. Two steel arches are connected to a post-tensioned (PT) frame consisting of two concrete tie girders and concrete end diaphragms. The arches are held in-plane by concrete knuckles located at each corner of the PT frame. Thirty (30) inclined steel hangers are installed at each arch to create the network arch. Since the bridge runs parallel to north-south direction, the arches are located on the west and east sides of the bridge. The hangers were labeled based on their location. The hangers at the west arch were labeled from WH1 to WH30, while the hangers at the east arch were labeled from EH1 through EH30.



(a) Plan view



(b) Elevation view

Figure 1: Primary elements of the bridge.

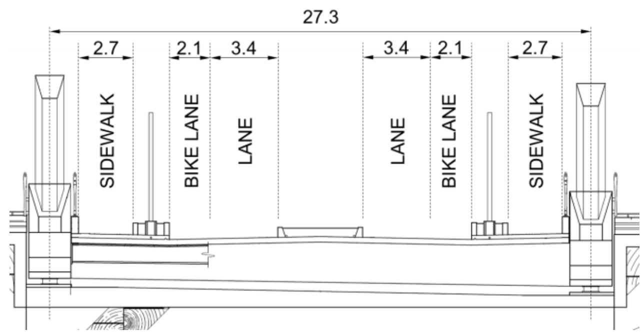


Figure 2: Typical bridge section. All dimensions are in m.

A linear elastic analysis was performed to investigate the hanger replacement scenario. The main goal of this analysis was to replicate the replacement of any arbitrary cable using the static method detailed in the Recommendation for Stay Cable Design, Testing and Installation manual (PTI 2018). According to PTI recommendations, the suggested load factors and combinations for the hanger exchange is:

$$1.2\,\mathrm{DC} + 1.4\mathrm{DW} + 1.5\,(\mathrm{LL} + \mathrm{IM}) + \mathrm{CEF} \qquad (1)$$

where:
DC = dead load of structural components and non-structural attachments
DW = dead load of wearing surface and utilities
LL = full vehicular live load placed in actual striped lane
IM = vehicular dynamic load allowance
CEF= cable exchange force

Since the analysis only used dead load, the live load component in Equation 1 is zero. In addition, time-dependent parameters of the concrete were taken into account during the analysis. Hence Equation 1 was modified as follows.

$$1.2\,DC + 1.4DW + 1.0\,(PS + CR + SH) + CEF \qquad (2)$$

where:
PS= secondary forces from post-tensioning for strength limit states; total prestress force for service limit states
CR= force effects due to creep
SH= force effects due to shrinkage

Models were analyzed for three skew angles: straight, 15°, and 20°. In addition, an 18° skew model was also analyzed to compare the results with the prototype bridge. Out of the 60 hangers, one hanger was released sequentially starting from WH1 to run 60 models for each skew angle. Axial force in the remaining hangers in each model was documented to evaluate the safety of the structure.

3. RESULTS AND DISCUSSION

The maximum and minimum forces in each hanger were documented and graphically presented in Figure 3 and Figure 4. As an example, Figure 3 shows the variation of the maximum and minimum hanger forces at the west arch of the 20° skew bridge while releasing the hangers at the same arch. As shown in the figure, the minimum force during hanger replacement remains closer to the forces of the as-built structure. The maximum force increase ranges from 26% to 43% compared to the as-built, except for the 2nd hanger closer to acute corner. Figure 4 shows the variation of the maximum and minimum hanger forces at the east arch of the 20° skew bridge while releasing the hangers at the west arch. As shown in the figure, hanger forces at the east arch are not impacted due to the operations at the west arch. As shown in Fig*ure* 5 and Fig*ure* 6, similar observations are recorded at the east and west arches while releasing hangers at the east arch.

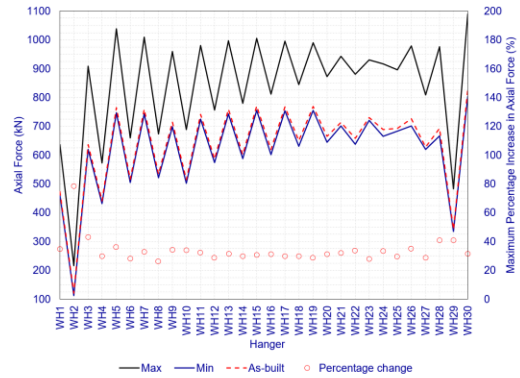


Figure 3: Hanger forces at the west arch of the 20° skew bridge while releasing the hangers at the west arch

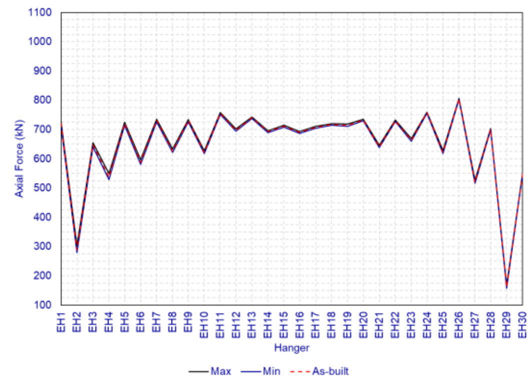


Figure 4: Hanger forces at the east arch of the 20° skew bridge while releasing the hangers at the west arch

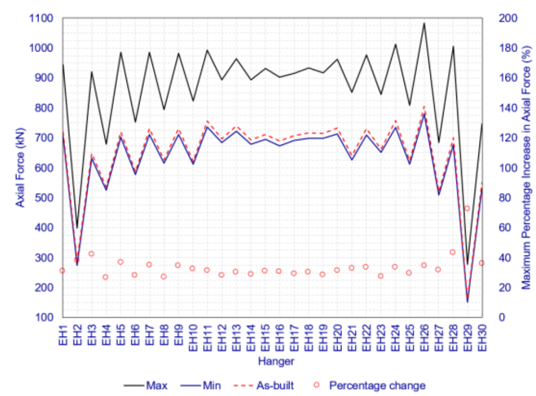


Figure 5: Hanger forces at the east arch of the 20o skew bridge while releasing the hangers at the east arch

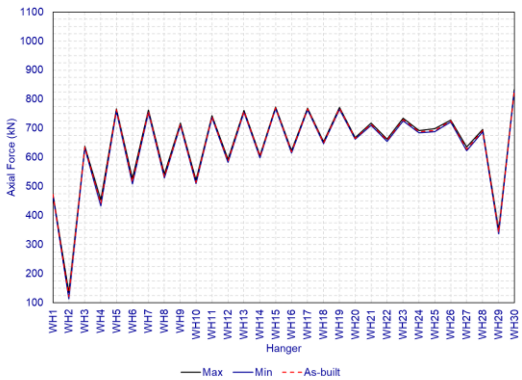


Figure 6: Hanger forces at the west arch of the 20o skew bridge while releasing the hangers at the east arch

Even though the percent increase in hanger forces remain same irrespective of the skew angle, the maximum increase in tension is only 53.4 kN compared to the hanger forces in the straight bridge. The observations indicate that the sequential replacement of hangers in a straight and moderately skew unbraced network arch bridges can be performed under its own weight without impacting the structural integrity.

4. SUMMARY AND CONCLUSIONS

This paper presents the results of a parametric investigation to develop a definitive procedure for determining the system factors for straight and moderately skew unbraced network arch bridges under dead loads.

The analysis results show that the maximum hanger force increase ranges from 26% to 43% compared to the as-built, except for the 2nd hanger closer to acute corner. However, the percent increase in hanger forces remains the same irrespective of the skew angle. The maximum increase in tension is only 53.4 kN compared to the hanger forces in the straight bridge. In addition, the analysis results show that the arches behaved independently and did not impact the hangers at the opposite arch during the cable release operation. The observations indicate that the sequential replacement of hangers in a straight and moderately skew unbraced network arch bridges can be performed under its own weight without impacting the structural integrity.

The results presented in this article are limited to the analysis of the structure under self-weight. This study will be continued to evaluate the structural redundancy in the presence of wind and live loads. Also, the impact of the abrupt hanger loss on the structural redundancy will be evaluated using both deterministic and probabilistic approaches.

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