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DECONSTRUCTION AND MAINTENANCE OF STEEL BRIDGE USING FATIGUE DATA AND BIM

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Abstract: Design for deconstruction is one of the emerging concepts for sustainability. For existing structures, the concept can be extended to optimize maintenance schedule for different components. Many existing steel bridges are at a stage in their lives where decisions need to be made to either continue in existing condition, to strengthen or to deconstruct them. This decision is highly dependent on the fatigue resistance of the steel connections which is a function of remaining structural strength, service load, expected future use and other environmental factors. Over the years a great deal of research work has been done in assessing the fatigue life of steel structures. This study utilizes these fatigue information to carry out a life cycle assessment of bridge elements and layer the system using BIM. As the BIM system will apply economic analysis for maintaining the bridge versus deconstructing and rebuilding of a new bridge, it will be instrumental to optimize the decision on any intervention in the bridge.

1 INTRODUCTION

A large number of steel bridges were constructed in the last 100 plus years and many of these bridges are still in operation. Many existing steel bridges are at a stage in their lives where decisions need to be made to either continue in existing condition, to strengthen them or to demolish them. The decision making process is dictated mainly by remaining serviceable life of the bridge. Fatigue is one of the key factors that need to be assessed in making decision about the bridges. The fatigue life, in turn, is a function of remaining structural strength, service loads, expected future use and other environmental factors. There exist many standards and approaches for bridge evaluation and one of the widely used approach is AASHTO (2011).

The construction and demolition industry accounts for 25-30 per cent and sometimes more than 50 per cent of the municipal solid waste in Canada (Yeheyis *et al*., 2012). Design for deconstruction is one of the emerging concepts for sustainability (Morgan and Stevenson, 2005; Shell *et al.* n.d.). As the structure, buildings, bridges and other infrastructure, constructed in the industrial boom of 20th century are coming to age, a comprehensive approach in assessing their remaining lifespan, function and re-usability is essential. Although the design for deconstruction has so far been limited to design of new buildings with view of optimizing deconstruction, the concept should be extended to sustainable use of existing infrastructure.

For existing structures, the concept of design for deconstruction should be extended to assess remaining life-span, optimize maintenance schedule for different components and increase function and life-span of the structures. Many existing steel bridges are at a stage in their lives where decisions need to be made to either continue in existing condition, to strengthen or to deconstruct them. This decision is highly dependent on the fatigue resistance of the steel connections which is a function of remaining structural strength, service load, expected future use and other environmental factors. Over the years a great deal of research work has been done in assessing the fatigue life of steel structures. This study utilizes these fatigue information to carry out a life cycle assessment of bridge elements and layer the system using BIM.

A fatigue evaluation in bridges involves numbers of uncertainties and the practice, in general, has been to assign a conservative fatigue life. The conservative consideration is reflected in the fact that “some bridges with satisfactory service history are accordingly determined to have negative remaining fatigue lives (NCHRP, 2012).” NCHRP (2012) mentions that “a number of factors may have contributed to this conservatism: overestimated load distribution factors, unintended composite action ignored, the S-N curve’s lower bound being used, etc.” However, not all cases of fatigue evaluation are believed to be overly conservative. For example, truss or two-girder bridges carrying more than one lane of traffic may have un-conservative fatigue life estimates because of the single lane loading prescribed in the MBE. When multiple lanes are carried by the two trusses or girders, the fatigue life may be significantly overestimated because possible simultaneous loads on other lanes are ignored (NCHRP, 2012).”

Maintenance and rehabilitation of the steel bridges require a comprehensive evaluation scheme for decision making. Building information modelling (BIM) "is a digital representation of physical and functional characteristics of a facility. A BIM is a shared knowledge resource for information about a facility forming a reliable basis for decisions during its life-cycle; defined as existing from earliest conception to demolition (NBIMS)." Overall scope of BIM, as outlined in NBIMS (2007), has three categories: BIM as product for digital data representation, BIM as a collaborative process and BIM as a facility lifecycle management tool. As BIM is gaining wider popularity in the construction industry, extension of its application in evaluation, maintenance and rehabilitation of bridges will be instrumental to support the decision making process. There already exist a number of such methods, schemes, tools and approaches for this purpose; however, a comprehensive BIM approach is still not completely developed.

This paper presents a scheme of applying BIM in assessing fatigue life of steel bridges and applying that information in BIM model to support decision making process. The system includes gathering field data, applying the data for create drawings, develop finite element models from the drawings, assessing fatigue life of the bridge and applying that information to make decision about status of the bridges.

2 INFORMATION MODELLING

The process used in the BIM is shown in the flow chart in Fig. 1. The first phase is the collection of data from existing bridges, and then using this information an AutoCAD drawing is creating that is representative of the bridge connection to be modeled. The AutoCAD drawing can be imported into a finite element modeling software such as AutoDesk Simulation Mechanical. The model is loaded and the necessary boundary conditions are applied and the stresses are obtained as the output from the finite element analysis (FEA) software. The elastic stress concentration factor is then obtained by dividing the maximum stress (in this case the maximum principal stress) by the nominal applied stress as used and proposed by Wokem (2010) and Pilkey (1997), respectively. Using this information the fatigue life at any instant of the bridge connection can be obtained and hence the remaining life of the bridge connection knowing the load history of the bridge. Decision can be made based on the remaining fatigue life of the connection whether to maintain or deconstruct the bridge. These decisions can be influenced by a lot of factors such as how many connections are near to the end of their fatigue life within the same bridge, cost of deconstruction, and importance of the bridge for traffic amongst others. The fatigue life of the connections will give very useful information to guide this decision making process.

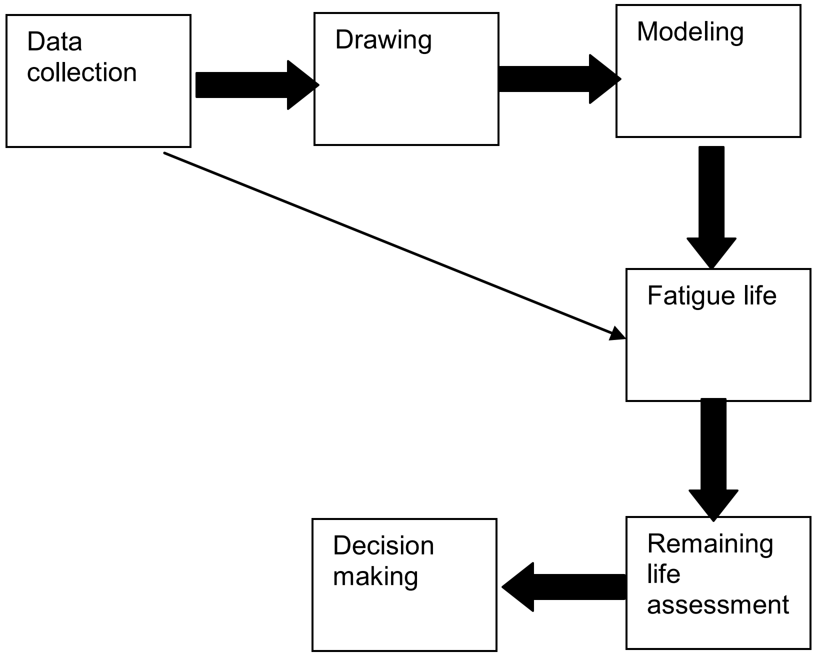


Figure 1: Schematic representation of the BIM model for fatigue life evaluation and decision making of existing steel bridge.

3 STEEL BRIDGE INFORMATION

For the purpose of this study, bridge samples constructed in early 20th century were considered. These bridges are constructed using riveted joints with or without staggered arrangement of the rivets (Fig 2 a, b).

Figure 2: Typical connection details in two steel bridges. a. Non-staggered rivets in the gusset plate; b. Staggered rivets in the gusset plate

Although presence of tack welds has significant effect in fatigue life of a riveted joint, the welds are not easily visible and their presence, strength and contribution cannot be easily ascertained. Furthermore, contribution of tack weld is to increase fatigue life resulting in conservative estimate of the remaining life. The effect of tack welds in this case is therefore not accounted for in this study. However, once the presence of tack welding and its effect is ascertained, it is a simple process to include that in the BIM process discussed in this paper here.

4 NUMERICAL AND ANALYTICAL MODEL

The drawings of the bridge connection as shown in Fig. 2 a. and finite element model of the same the same connection are shown in Fig. 3. Drawing, in this study, has been accomplished using AutoCAD and the finite element modeling is done using Autodesk Simulation Mechanical.

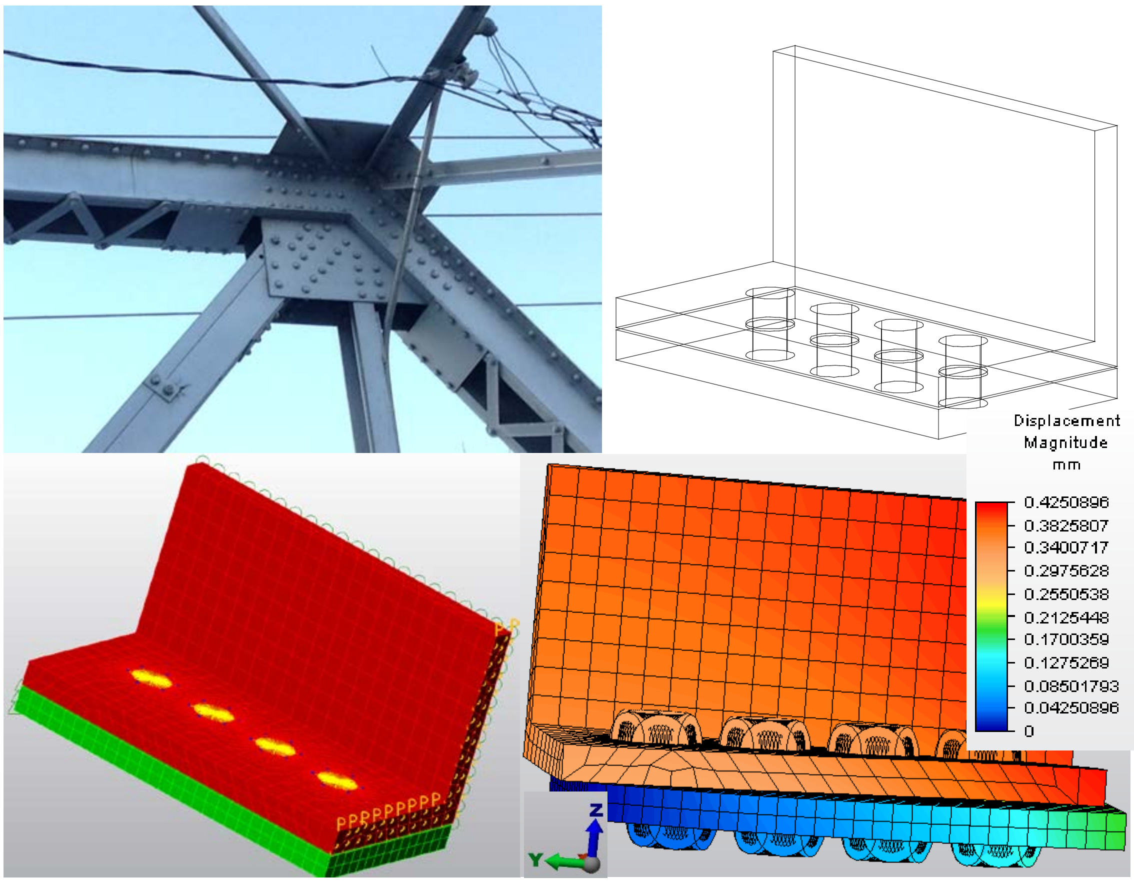


Figure 3: A typical rivet connection in a steel truss bridge is drawn in AutoCAD, exported to Autodesk Simulation Mechanical for FEA to obtain stress and strain information.

4.1 Model geometry and the material properties

The typical angle connection of a bridge was modeled in AutoCAD. The equal leg angle connection had a dimension of 102 mm and a thickness for the angle was 12.7 mm. The gusset plate had a thickness of 12.7 mm. The analysis was elastic. The material properties used in the modeling was; Young's modulus of 200,000 MPa and a Poisson's ratio of 0.29. The rivets were modeled using the bolt command in the Autodesk Simulation Mechanical and a rivet diameter of 20 mm was used and a rivet head of 25 mm was specified for the simulation.

4.2 Finite element mesh

The angle and the gusset plate were modeled using a plate element. The rivet hole had a finer mesh size of 1 mm and the other parts of the connection detail were modeled with coarser mesh. The finer mesh was used around the rivet hole because the maximum stress is expected to occur in these holes rather than in any other part of the connection.

4.3 Load and boundary conditions

A stress of 200 MPa was applied to one end of the angle and the gusset plate. The gusset plate had the other end fixed. The leg of the angle that was not attached to the gusset plate was restrained from translating in the z-axis and the x-axis, and also there was no rotation about the y-axis in the leg. The angle leg attached to the gusset plate was not restrained at all.

4.4 Finite element analysis result

Fig. 4 shows the finite element analysis result for the bridge detail. A maximum principal stress of 706.51 MPa was obtained for an applied load of 200 MPa. The maximum principal stress occurred in the gusset plate and at the first hole closest to the point of application of the tensile stress in the detail. The results show that the first and the last holes had the highest stress concentration.

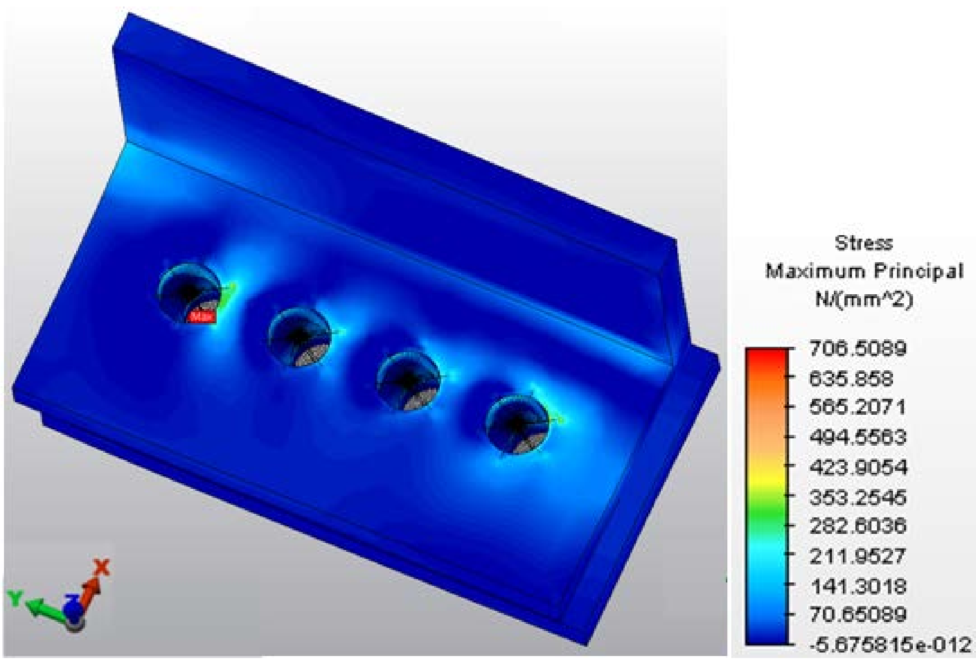


Figure 4: FEA model showing location of maximum principal stress

5 FATIGUE ANALYSIS

Autodesk Simulation Mechanical was used to obtain the maximum stresses and hence the stress concentration was obtained by dividing the maximum principal stress in the detail by a nominal applied stress, and fatigue strength of the typical connection type shown in the Fig. 3.
The output from the finite element analysis and calculation of fatigue life as proposed in Bannantine *et al*. (1990) is shown below.

Calculations for the fatigue Life
Applied stress on the FEA = 200 MPa
Maximum Principal stress = 706.51 MPa (Obtained from FEA)
Maximum von Mises stress = 712.34 MPa (Obtained from FEA)
Ultimate strength of Steel = 400 MPa = S_u
K_t = Max principal stress/gross section stress = 3.53
Assume notch sensitivity factor of q=1, therefore $K_f = K_t = 3.53$
For Steel (from Bannantine *et al*. 1990):
at 1000 cycles, $S_{1000}=0.9S_u$ = 360 MPa
at 1000000 cycles $S_e = 0.5\ S_u$ = 200MPa

Now accounting for the stress concentration from the FEA the new S-N curve becomes

Table 1: S-N data for connection

Fatigue Life, N (Cycles)	Stress, S (MPa)
1,000,000	56.66
1,000	101.98

Using the new S-N (from Table above) and the following equations (Bannantine *et al.* 1990) the fatigue life can be obtained:

[1] $N = 10^{-c/b} S^{1/b}$

[2] $C = log \frac{S_{1000}{}^{2}}{S_e}$

[3] $b = -0.333 log \frac{S_{1000}}{S_e}$

A hypothetical case is shown below as an example to demonstrate fatigue life of a bridge.

A bridge has the connection type modeled; the loading in the bridge was converted to an equivalent fully reversed stress of 70 MPa. What will be the life of the bridge at this time given that it is subjected to 1000 equivalent constant stress cycles per year?

<u>Solution</u>

From the equations above

C = 2.264, and b =-0.085

Hence N = 8.48×10^4 cycles

Therefore the bridge fatigue life is 84.8 years. The S-N curve for the detail is shown in Fig. 5. If the same bridge is subjected to an equivalent fully reversed stress of 69.02 MPa, then either by using Eq.1 or the S-N curve in Fig. 5, the fatigue life of that detail is 100 years given the same stress cycles per year of 1000.

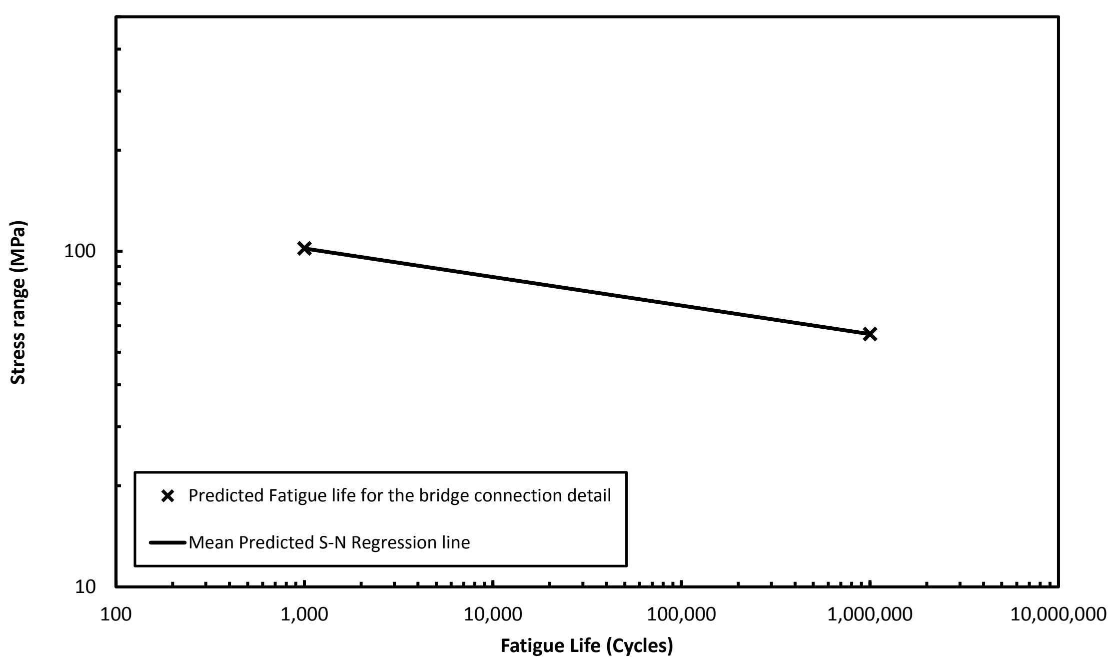


Figure 5: S-N curve for the bridge connection detail

6 BIM MODEL

Building information modelling (BIM) "is a digital representation of physical and functional characteristics of a facility. A BIM is a shared knowledge resource for information about a facility forming a reliable basis for decisions during its life-cycle; defined as existing from earliest conception to demolition (NBIMS)." In this paper a combination of picture representation, drawing and FEM tools (AutoCAD and AutoDesk Simulation Mechanical from AUTODESK) and spreadsheet (MS-Excel) is used to represent the data, to analyze the stresses and to evaluate the life-cycle of a typical rivet connection of a steel bridge. The schematic diagram is shown above in Fig. 3 and a screen capture from spreadsheet is shown below in Fig. 6.

Life-cycle assessment of steel bridges : Fatigue Analysis

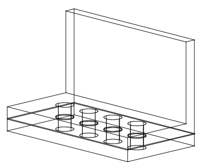
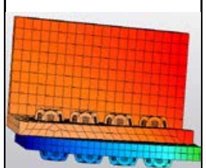
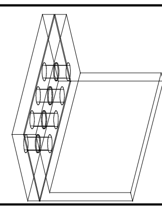
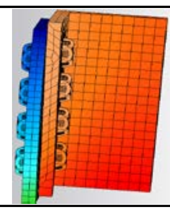
Joint	Picture	Drawing	Analytical model	Stress concentration factor	Equivalent stress	Stress cycle	Bridge fatigue life	Remaining life
1				3.53	70 MPa	1000	84.8	4.8
2				3.53	69 MPa	1000	100	20 yrs

Figure 6: A schematic model showing hypothetical case of two typical bridge connections and calculation of remaining life from fatigue analysis. In this example, considering a hypothetical case in which the bridge has served 80 yrs of life, joint 1 has 4.8 yrs remaining life and joint 2 has 20 yrs remaining life. Joint 1 is critical needs immediate attention

7 DISCUSSION AND CONCLUSION

As the structure, buildings, bridges and other infrastructure, constructed in the industrial boom of 20th century are coming to age, a comprehensive approach in assessing their remaining lifespan, function and re-usability is essential. Although the design for deconstruction has so far been limited to design of new buildings with view of optimizing deconstruction, the concept should be extended to sustainable use of existing infrastructure. BIM, which is not only data representation and storage system but also a life cycle management tool, needs to be extended to assess remaining life of infrastructure which will help in decision making of the continuing use of the infrastructure. In this paper a model is presented to analyze remaining fatigue life of bridge using drawing tools, Finite element analysis tools and spreadsheet application in assessing critical joints for bridges. The model can be further extended to include other factors such as serviceability condition, existing condition of infrastructure and functionality of the structures before making a final decision on how to optimize life-cycle of the infrastructure in question. In a bridge the is invariably going to be several connection details, and hence a BIM system is essential to track the connection type, the stress concentration, the fatigue life, and hence information on maintenance or deconstruction can be made in time.

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