LOCAL BUCKLING ANALYSIS OF STEEL TRUSS BRIDGE UNDER SEISMIC LOADING

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Abstract

In the 2004 Mid Niigata Prefecture Earthquake, a steel truss bridge was damaged: the lower chord member underwent local buckling. The axial force in that member is not necessarily compression-dominant: tensile axial force is also expected. Since many steel bridge piers were subjected to local buckling in the 1995 Kobe Earthquake, the criterion for local bucking in the member under axial compression has been studied rather extensively. However, the local buckling in the member under the other states of axial force has not. In the present study, the local buckling in the lower chord member of a truss bridge is to be looked into. To that end, the existing criterion for local buckling in terms of average strain is tested for the case when tensile yielding precedes compression, failing to confirm its applicability. Then the criterion is modified by introducing the updated average strain. The seismic response analysis is then conducted to show the significance of the proposed criterion.

Introduction

One of the largest earthquakes in the recorded history, the Tohoku Earthquake, just hit Japan in March, 2011, causing very serious damage in the eastern part of Japan. Yet the memory of the damage to structures in the 1995 Kobe Earthquake is still fresh and vivid for many structural engineers. Between the two large earthquakes, numerous earthquakes occurred as well, some of which were quite large and comparable to the 1995 Kobe Earthquake. The damage in each big earthquake has posed a new challenge for engineers; some of them are yet to be solved.

In the 2004 Mid Niigata Prefecture Earthquake, a steel truss bridge was damaged: the lower chord member underwent local buckling at its fixed end. The axial force in that member is not necessarily compression-dominant: tensile force can be expected. Since many steel bridge piers experienced local buckling in the 1995 Kobe Earthquake, the criterion for local bucking in the member under axial compression has been studied rather extensively (Ono et al. 2007, Committee 2008). However, the local buckling of the member under the other states of axial force has not. In the present study, the local buckling in the lower chord member of a truss bridge is to be looked into.

Existing Criterion for Local Buckling

Local buckling can be simulated in the finite element analysis (FEA) with shell

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elements. Even though it is not impossible to model the whole bridge by shell elements and conduct nonlinear dynamic FEA, that is not a practical approach to structural design; beam elements are employed exclusively for the analysis of seismic design. However, since the cross section of a beam element does not deform, the direct simulation of the local buckling by beam elements is not possible. To overcome the difficulty, various efforts have been made, which includes the detection of the local buckling by the magnitude of strain (Ono et al. 2007, Committee 2008) and the implementation of strength reduction due to local buckling in the constitutive relationship (Yamaguchi 2009).

The criterion of the local buckling due to Committee (2008) is based on the average strain ε in a compressive flange over the characteristic length L_C. For a box-section member, the characteristic length L_C is given by

$$L_C = Min(0.7b, a) \tag{1}$$

where a is the distance between two adjacent diaphragms and b the width of a flange. *Min* indicates that the smaller of the two values in the parenthesis shall be taken. On the other hand, the limit strain ε_u for an unstiffened box-section member is computed by

$$\left|\frac{\varepsilon_u}{\varepsilon_y}\right| = \frac{0.24}{\left(R_f - 0.2\right)^{2.8}\left(1 + N_c/N_y\right)^{2.4}} + \frac{2.8}{\left(1 + N_c/N_y\right)^{0.6}} \leq 20.0 \tag{2}$$

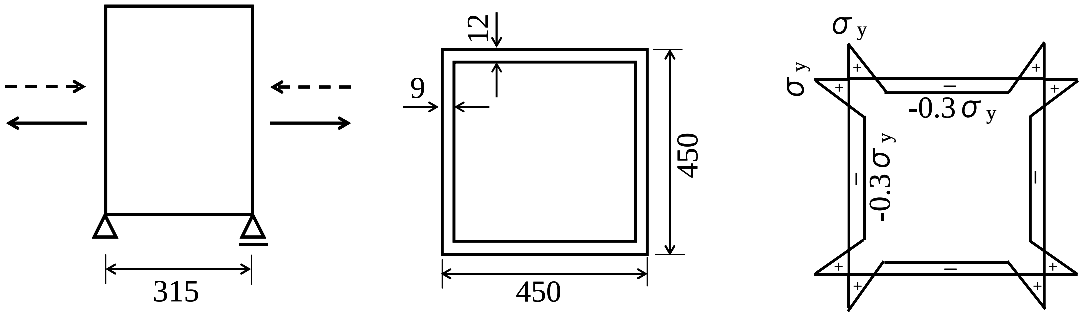
where ε_y is the yield strain, R_f the width-to-thickness ratio parameter, N_C the compressive axial load and N_y the squash load. The validity of the equation has been verified for $0.2 \leq R_f \leq 0.7$, $0.0 \leq N/N_y \leq 1.0$.

The criterion for the local buckling is then that the member is judged to undergo local buckling at the instance when the average strain ε reaches the limit strain ε_u. It is noted that N_C changes during earthquake so that the limit strain ε_u varies with time as well.

Equation 2 has been obtained under compressive loading applied monotonically. Therefore, the validity of Equation 2 is not clear if tensile yielding precedes compression. The investigation is needed herein since the lower chord member in a truss bridge may yield in tension.

To this end, a short box-section member shown in Figure 1 is constructed. It is pulled first and then compressed until local buckling occurs. This nonlinear problem is analyzed by ABAQUS (Dassault 2008) using 1280 shell elements: the local buckling can be simulated directly. The material is steel with Young's modulus E equal to 2.0×10^5 N/mm^2 and the yield stress σ_y equal to 235 N/mm^2. The stress-strain relationship is of a bilinear type with the slope after yielding being $E/100$ (Figure 2).

Six cases are considered, between which the difference lies in the initial



unit: mm

(a) Side view (b) Cross section (c) Residual stress

Figure 1 Short box-section member

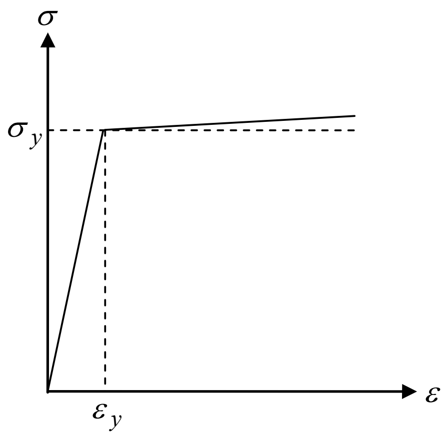


Figure 2 Stress-strain relationship of steel

elongation: the maximum initial tensile strain ε_t in the six cases are $\varepsilon_t = 2\varepsilon_y$, $3\varepsilon_y$, $4\varepsilon_y$,, $5\varepsilon_y$, $7\varepsilon_y$, and $10\varepsilon_y$, respectively.

The average strain ε at the initiation of the local buckling in each case is presented in Figure 3. The limit strain ε_u is also given in the same figure. Note that the limit strain ε_u is common to all the cases since Equation 2 has nothing to do with the maximum initial tensile strain ε_t.

Significant difference between ε and ε_u is observed. When the initial elongation is large, the local buckling occurs, even when the average strain ε is still tensile. This result shows that the criterion with the average strain ε and the limit strain ε_u given by Equation 2 is not valid if tensile yielding precedes compression.

Proposed Criterion for Local Buckling

Once an elastic-plastic material yields, strain does not vanish even when all the loads are removed completely. However, upon reloading, the material behavior would be similar to that of the original material except that the subsequent yield point may be

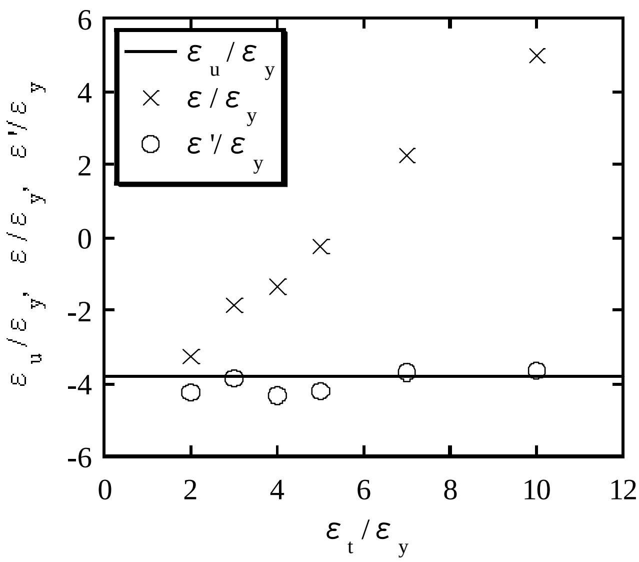


Figure 3 Average strain ε and updated average strain ε' at instance of local buckling after pre-yielding ε_t

different from the initial value according to the plasticity theory (Chen 1994).

Likewise, once a steel member elongates beyond the yield point, deformation remains even when all the loads are removed completely. Yet, the member behavior would be similar to that of the original member except that the subsequent yielding occurs at different loading level.

This observation suggests that instead of the average strain ε, the updated average strain ε' should be used for the comparison with the limit strain ε_u to see if local buckling occurs. The definition of the updated average strain ε' is given schematically in Figure 4: the origin of the updated average strain ε' is located at the state of the complete removal of stress.

To verify the validity, the updated average strain ε' at the instance of the local buckling is obtained in the analysis of the short box-section member for the six cases mentioned above. The results are presented in Figure 3. The updated average strains ε' at the local bucklings are in good agreement with the limit strain ε_u given by Equation 2.

It is then proposed that the updated average strain ε' instead of the average strain ε is to be compared with the limit strain ε_u in Equation 2 for the judgment on the initiation of local buckling. Needless to say, the proposed criterion is also good for monotonic loading, since the updated average strains ε' is nothing but the average strain ε under monotonic loading.

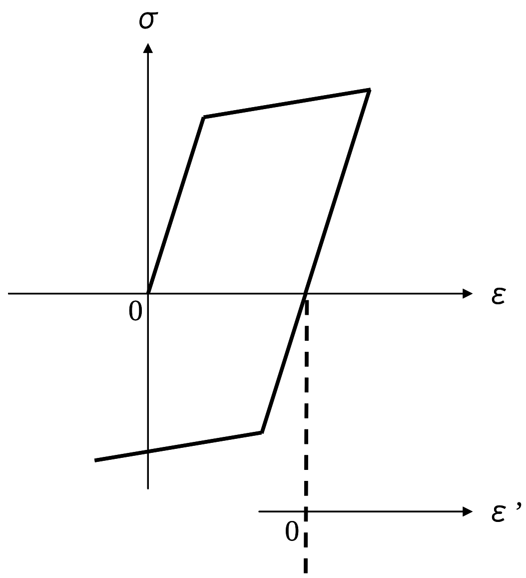


Figure 4 Schematic definition of updated average strain ε'

Seismic Response of Truss Bridge Model

Figures 5 and 6 show a truss bridge model to be analyzed in the present study. It is a simply-supported bridge with the length of 74.4 m. The bridge end denoted by A in Figure 5 is fixed longitudinally. The truss members are made of steel that has the same material properties as those of the short box-section member including the stress-strain relationship (Figure 2). The floor slab is concrete and 220 mm thick. Young's modulus of concrete is 1/7 of that of steel, and the stress-strain relationship is shown in Figure 7 where ε_0 is 0.002, ε_{cu} 0.0035, σ_{ck} 30 N/mm^2.

The time history of seismic acceleration in Figure 8 is applied. This is an actual seismic data recorded in the 2004 Mid Niigata Prefecture Earthquake. Dead load is also considered simultaneously.

Using the model mentioned above, nonlinear dynamic analysis is conducted by the finite element software Y-FIBER3D (Yamato 2000) to obtain the seismic response of the truss bridge.

Figure 9 (a) shows the numerical result where the average strain ε in the lower chord member near the bridge end A together with the limit strain ε_u is presented. Note that the cross section of the bridge end A is the same as that given in Figure 1 (b). The average strain ε fluctuates and is compressive from time to time at the initial stage, but tensile strain dominates at the later stage. The average strain ε and the limit strain ε_u do not cross, indicating that the local buckling does not occur if the average strain ε is used for the judgment.

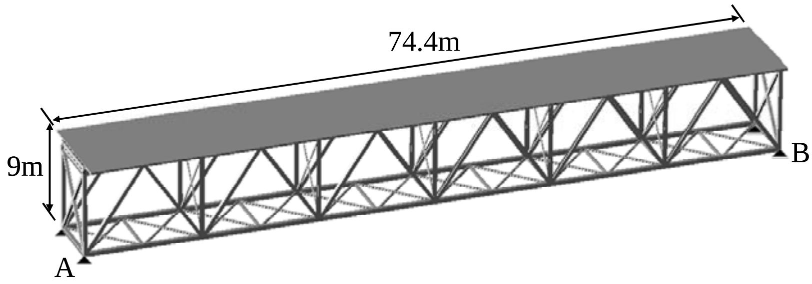


Figure 5 Schematic of truss bridge model

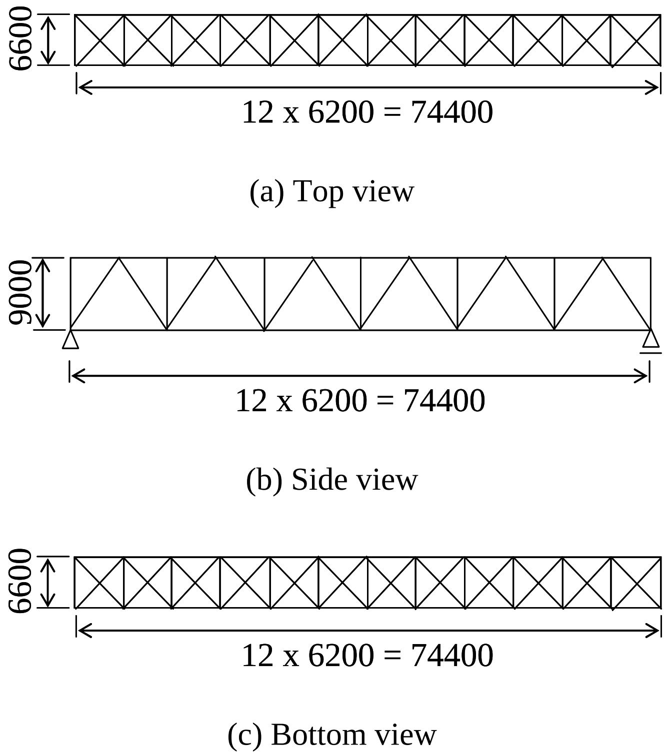


Figure 6 Main truss (Unit: mm)

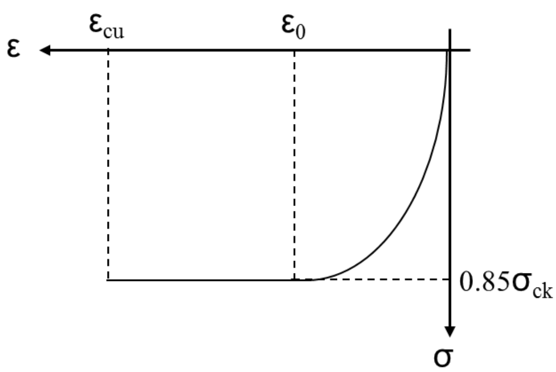


Figure 7 Stress-strain relationship of concrete

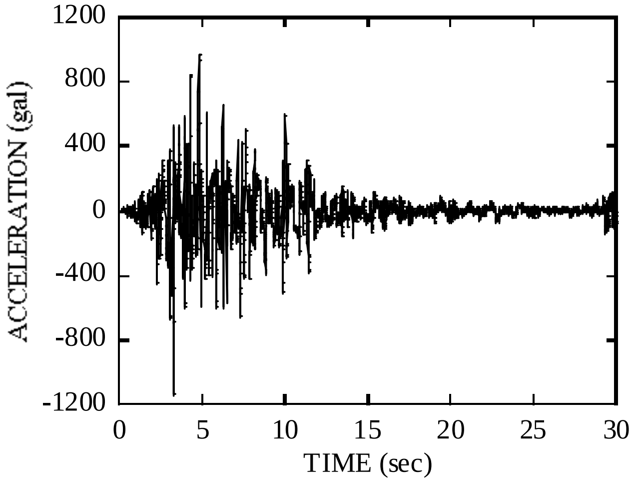


Figure 8 Acceleration recorded in 2004 Mid Niigata Prefecture Earthquake

The updated average strain ε' is plotted in Figure 9 (b). It is very different from the average strain ε in Figure 9 (a): the updated average strain ε' does meet the limit strain ε_u so that the local buckling is judged to take place. The significance of the proposed criterion is thus obvious.

Concluding Remarks

When beam elements are employed for the seismic response analysis of a bridge, the criterion for local buckling is necessary. However, it has been concluded in the present study that when tensile yielding preceded, the existing criterion could not give the correct judgment.

The modification of the criterion in which the average strain was replaced by the updated average strain has been proposed. The seismic response analysis of a steel truss bridge then demonstrated the significance of the proposed criterion.

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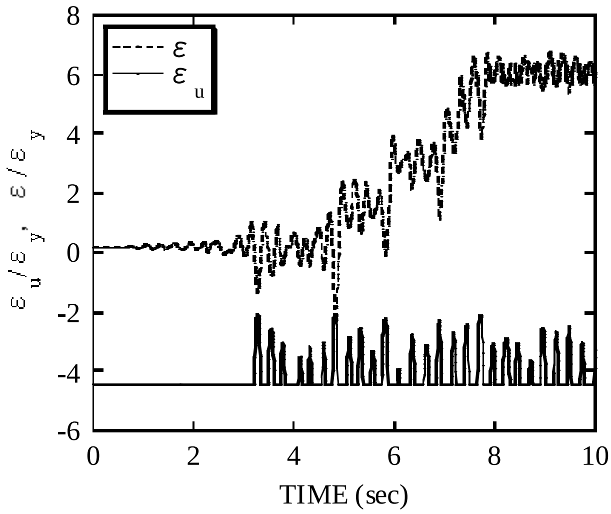
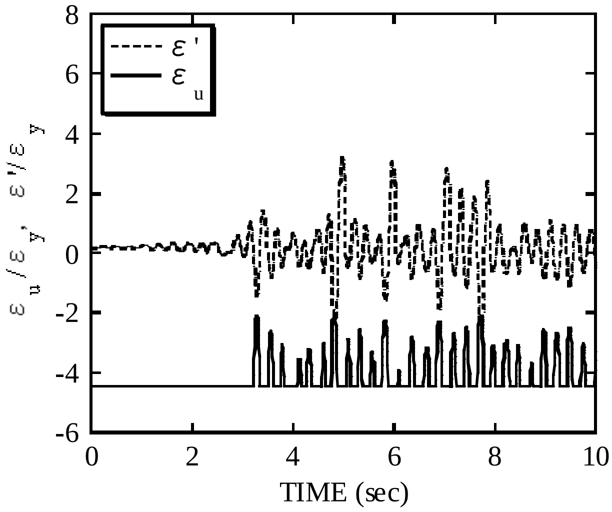


(a) Average strain ε and limit strain ε_u



(b) Updated average strain ε' and limit strain ε_u

Figure 9 Variation of strain with time

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