Imperfection Sensitivity Laws for Elastic and Plastic Buckling of Bridge Structures Subjected to Random Traffic Loads

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論文内容要旨

The dependence of the structural performance on imperfection parameters is evaluated by imperfection sensitivity analysis. The imperfection sensitivity in buckling problems has been the subject of numerous analytical and numerical studies. The asymptotic manipulation, a common analytical treatment for imperfection sensitivity, seems to have limited use to simple structures due to the complexity of such methods[1), 2)]. That limitation stands as an obstacle faces the practice usage of imperfection sensitivity laws. Studying the performance of bridge structures under varied traffic loading conditions is an example of engineering problems. Load variation has come to be employed in structural design through the probability-based load criteria[3)]. Since the late of 1960s, many uncertainties could be modeled probabilistically and several probability codes were suggested[4)]. In the probability-based load criteria, the safety criteria generally does not depend only on the ratio of the nominal value of the actual load and the maximum load, but also on the variations of both actual and maximum loads. A higher value of the safety factor seems to indicate a safer structure. However this is not necessarily the case as the inevitable variations in both actual and maximum loads must be kept in mind. The sketch shown in Fig. 1 illustrates that the factor of safety are greater than one based on nominal values, but because of the relatively large variations in both actual and maximum loads, there is a significant probability that the actual load exceeds the maximum load, and cause failure. Even though accurate assessment of loads that the bridge is subjected to is an important requirement for the design and evaluation purposes of bridges, only simplified traffic load models are used for bridge design and evaluation. The traffic load that is used for deriving such models is not based on the actual traffic data which passes over the bridge, but an idealized and simplified one.

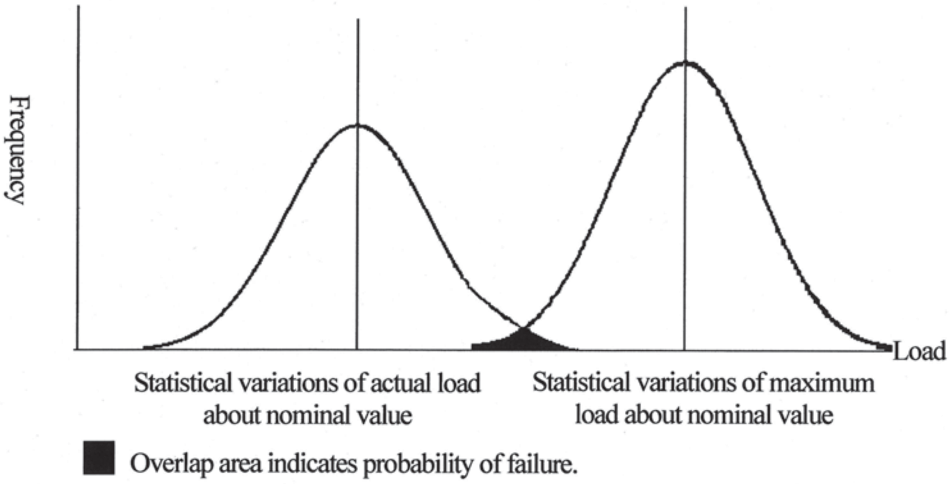

Figure 1 Effect of the load variation on the safety criteria.

One of the significant difficulties in using the actual traffic data is to conduct a probabilistic analysis of buckling strength for the bridges in presence of such numerous sets of traffic loading data. The classical numerical simulations such as Monte Carlo simulation, which is usually used for conducting that probabilistic analysis, are computationally very costly.

The first objective of this research is to develop a simple and robust method to conduct a statistical buckling analysis of bridges subjected to traffic loading in the framework of imperfection sensitivity laws.

In this research, the imperfection sensitivity law is extended twofold:

- To be applicable for practical engineering use such as buckling strength analysis of bridge structures subjected to varied traffic loads.
- To be used for elastic–plastic buckling analysis.

Imperfection sensitivity analysis of elastic–plastic systems has been the focus of extensive numerical and analytical studies. Some researches extended the use of the asymptotic analytical techniques to the elastic–plastic analysis of simple structural problems. The difficulties to develop a robust methodology to tackle such sensitivity mechanisms have been pointed out by Hutchinson[5] and Byskov[6], such complexity is due to the considerable complication that accompany with the presence of the elastic–plastic behavior.

In this research, the author aims to develop a simple and robust method to conduct statistical analysis of buckling strength for bridge structures subjected to traffic loading in the framework of the imperfection sensitivity laws.

For this purpose:

- The two-third power law of Koiter, which is known to describe the buckling strength against an initial imperfection in elasticity, is introduced in a simple explicit form,
- The simplified form is generalized to be applicable to the case where large number of varied imperfection parameters

is applied.

- The generalized formula is employed in a probabilistic buckling analysis procedure.
- The imperfection sensitivity of some elastic–plastic structures is investigated.
- Asymptotic imperfection sensitivity formulas are presented, imitating Koiter sensitivity laws.
- These formulas are employed as a simple and robust tool to study the buckling sensitivity in elastic–plastic analysis.
- Probabilistic analysis for the buckling strength of bridge structures subjected to traffic load variations is conducted using the presented formulas.

By using the proposed procedures, straightforward and low-cost computational buckling analysis can be conducted for elastic–plastic bridges in the presence of traffic load variations data.

This thesis is organized as follows:

In Chapter 2, a brief mathematical overview on the stability analysis of the elastic conservative systems is introduced, and the imperfection sensitivity analysis in elastic stability is reviewed. Attention is paid towards reviewing the Koiter imperfection sensitivity laws as an established concept for the imperfection sensitivity analysis of elastic systems. Three points of concern in this research have been reviewed in Chapters 1 and 2, the first one is related to the usage difficulties of the imperfection sensitivity laws, the second concerns with the computational cost that is required in conducting the statistical buckling analysis of bridges subjected to traffic load variations, and, the third concern is the difficulty that faces the elastic–plastic buckling analysis in presence of imperfections.

In Chapter 3, the imperfection sensitivity law is introduced in an explicit form for a single parameter of imperfection. The imperfection sensitivity analysis of simple structures is conducted using the proposed formula, its results are compared with the finite element (FEM) analysis results, and the good agreement between the results assures the validity of the formula. Next, that proposed formula is generalized to multi-parameters imperfection. The generalized formula is examined numerically and its applicability is justified in the same chapter.

In Chapter 4, the generalized form is employed in a probabilistic analysis procedure. That procedure is applied in conducting a statistical buckling analysis of some truss structures subjected to normally distributed random external loads. The efficiency of that procedure in such probabilistic analysis is approved comparing with the Monte Carlo simulations.

In Chapter 5, the generalized formula is utilized to conduct the statistical buckling sensitivity analysis of an arch truss bridge structure subjected to 10,000 sets of random varied traffic loading data. The buckling sensitivity analysis for the same structure under the same traffic loading data is conducted through FEM analysis. The results of the proposed procedure and the FEM analysis are in a good agreement.

In Chapter 6, the imperfection sensitivity of several structures in the plastic range is investigated looking for simple asymptotic sensitivity formulas in order to conduct an efficient probabilistic buckling analysis of elastic–plastic bridges subjected to real random traffic loads. In that chapter, the buckling behavior of several bilateral symmetric elastic–plastic structures is investigated. Asymptotic imperfection sensitivity formulas are introduced to describe these behaviors. Their validity for single imperfection is declared, then, they are generalized to be applicable to several imperfection parameters. The traffic load variations are interpreted as imperfections, and the validity of the proposed formulas in investigating the buckling load against random traffic is verified.

Despite the accuracy of the proposed procedures, their performance can save large amount of computational time and resources. The superiority of the proposed method can be demonstrated by comparing its computational time with the ordinary methods. The proposed method decreases the computational cost considerably, which will help engineers and researchers to conduct sensitivity analysis in shorter time with almost the same accuracy as conventional methods.

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論文審査結果の要旨

本論文では，初期感度解析により，構造系の初期不整感度敏感性を評価している．構造系の座屈問題に関しては，数多くの研究がなされてきたが，その初期不整感度は，定式化が煩雑であるために，その適用例は，簡単な構造物に限られていた.

本論文では，様々な外力を受ける道路橋の座屈強度評価を，初期不整感度解析の代表的な工学的適用例としてとりあげる．この論文では，座屈強度の確率変動を初期不整感度則により記述する簡便な方法論を導出し，交通荷重を受ける道路橋の座屈強度評価に適用し，有用な結果を得ることに成功した.

本論文は下記のように構成されている.

- 第１章では，弾性保存系の安定問題に関する既往の研究のレヴューを行う．このとき，弾性問題に対する学問体系の初期の整備と，弾塑性問題への初期不整感度則の拡張について力点を置いている.

- 第２章では，Koiter による初期不整感度の誘導についてまとめ，あわせて，この手法が大規模構造系の工学的な適用が何故困難であったかについてまとめる.

- 第３章では，従来，１個の初期不整変数について定式化されていた初期不整感度則を，多変数に拡張・一般化する．このように拡張・一般化された初期不整感度則を構造系の座屈強度の評価に適用する.

- 第４章では，一般化した初期不整感度則を用いて，構造系の座屈強度の確率変動の評価法を定式化する．正規分布に従う外力を受けるトラス橋を適用例として取り上げ，Monte Carlo シミュレーションにより，一般化した初期不整感度則の妥当性を検証した.

- 第５章では，実構造例としてトラスアーチ橋を取り上げ，１００００組の実測交通荷重に対して，その座屈強度の確率変動の評価を一般化した初期不整感度則により行った．この構造系の座屈強度の初期不整感度を一般化則により評価し，有限変形FEM解析による結果と比較することにより，その妥当性を検証した.

- 第６章では，一般化した初期不整感度則を弾塑性座屈解析へと拡張し，実橋の弾塑性座屈強度の評価に適用し，その有用性を示した.

よって、本論文は博士(工学)の学位論文として合格と認める。