Reliability Analysis of Steel Moment-Resisting Frame Structure under the Light Vehicle Collision

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ABSTRACT

The Impact induced by vehicles collision to external buildings' columns is one of the research scenarios of collision. Therefore, in this study, the reliability analysis of steel moment-resisting frame structure with 2-story has been conducted under the impact of light vehicle collision considering uncertainty in material and applied loads using simulation-based methods. The mentioned structure is modeled in *OpenSees* software two-dimensionally and the sensitivity analysis of the studied random variables is performed using Monte Carlo simulation-based method in *Matlab* software. Then, the limit state functions are proposed based on the maximum permitted beam rotation of damaged bay. Finally, the failure probability and reliability index of the mentioned frame is investigated and compared according to performance levels under the impact of light vehicle collision with speeds 20, 40, 60 and 80 *Km/h*. The results showed that the random variables such as mass and velocity of vehicle and yield strength of material were the most influential variables in the failure probability and the control variates-based subset simulation method compared to Monte Carlo method estimated the failure probability with permissible error rate, less sample number and short running duration.

KEYWORDS

Reliability, Steel Moment-Resisting Frame, Light Vehicle Collision, Simulation-Based Methods, Sensitivity Analysis.

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1. Introduction

In the last decade, due to the increasing terrorist threats in different parts of the world, much attention has been paid to the design and analysis of resistant structures against abnormal loads. Traditionally, structural engineers designed and analyzed buildings against conventional lateral loads such as earthquake and wind, but in some cases, the study of the nonlinear performance of structures against abnormal loads such as vehicles impact and blasts are also important [1]. With regarding to assurance to performance of structures has always been an important principle for engineers and designers, and since complete assurance to the quantity of a potential natural or unnatural accident is not possible, the use of probabilistic analyses, Reliability with the application of various uncertainties such as geometry, materials, applied loads, etc are considered logical [2]. Some researches had been conducted in this field. Park et al. [3] analyzed the sensitivity of a steel moment- resisting frame due to column removal. Monte Carlo Simulation method (*MCS*) and the First-Order Second Moment method **(***FOSM*) have been used. The results showed that the random variable of yield strength of beam was the most effective parameter in the design of the frame under the effect of column removal. Kim et al. [4] evaluated the behavior of *3*-story steel moment- resisting frame structure under the effect of vehicle impact to the external corner by fragility curves with different velocities. Santos et al. [5] investigated the failure of common types of beam-column joints of the steel moment- resisting frame subjected to vehicle impact and the results showed that the reduced beam connection (*RBS*) caused the beam yielding mechanism and had better performance against impact loadings.

In this study, the probabilistic framework is proposed based on reliability of the steel moment- resisting frame under the effect of a light vehicle impact with different collision velocities (*20*, *40*, *60* and *80 Km/h*) using simulation methods Monte Carlo Simulation (*MCS*), Importance Sampling (*IS*), Subset Simulation (*SS*), Line Sampling (*LS*) and Control Variates-based Subset Simulation (*CSS*) and then the accuracy of these methods was measured by *MCS* method and Finally, an estimation of the probability of failure is obtained.

2. Methodology

In this study, a *2*-srory three-dimensional structure with a lateral bearing system of steel moment- resisting frame with intermediate ductility in both longitudinal and transverse directions is considered. This structure is designed based on Iranian design regulations (Codes *6* and *10* of National Building Regulations [6, 7]) and Standard No. *2800*, *4*th Edition [8] on soil type *II* in a very high risk zone (*A = 035 g*) with *ETABS* software [9]. It is designed by *LRFD* method. Dead and live loads of stories are applied at *500* and *200 kg/m*^{2}, respectively, and the critical criterion in designing the model of the building is drift. By examining the results, the ratio of demand to capacity in all its structural elements were far less than one. The two-dimensional frame of the side axis is extracted and modeled for nonlinear dynamic analysis under impact loads in *OpenSees* software [10]. Dead and live loads applied to the mentioned frame are *1500* and *600 Kg/m*, respectively, and the used steel materials in the beams and columns are *ST37* type with the values such as an elasticity modulus *200,000 MPa*, a yield stress *240 MPa* and a ultimate stress *370 MPa* are considered. Then, two-line uniaxial steel materials with kinematic and isotropic hardness are assumed based on *Steel01* model with a hardness of *3%* [3]. Therefore, the probabilistic analyses are conducted based reliability by *Matlab* software [11].

3. Results and Discussion

The *MCS* method was used to calculate the probability of failure. For this purpose, at first, the existing samples in the area of health and failure are identified and then, the limit state functions of the reliability problem are evaluated by performing nonlinear dynamic analyses. In each structural analysis, the random variables defined based on the selected probabilistic distribution. The studied random variables are classified into *4* categories including gravity loading, steel materials, geometric characteristics and impact loading due to the light vehicle collision. These variables included: yield strength, Poisson ratio, specific weight, damping ratio and elasticity modulus of the used steel material, the damaged beam length, the damaged column height, live, dead and impact loads.

In the following, the proposed limit state functions (*LSFs*) is considered based on the maximum permitted beam rotation of damaged bay according to Table 1 [4, 12]. These limit states and failure criteria related to three damage levels of steel structures subjected to extreme loads are presented as low, medium and severe damage states.

Table 1. The failure criteria of steel structures subjected to impact loads [4, 12]

Element	Failure Type	Damage Level Based on Rotation (Rad)		
		Low	Medium	Severe
Beam	Bending	0.05	0.12	0.25

At first, sensitivity analysis is performed by calling *100,000* times as a limit state function and evaluating the rate of failure probability change versus to the changes of each random variable and the results of sensitivity analysis showed that the uncertainty parameters such as vehicle mass, vehicle velocity, yield strength of the sections and the dead load of the frame had the maximum effect and Poisson ratio, specific weight of the sections and live load of the frame had the minimum effect on the calculation of the failure probability.

Then, the failure probability of the frame using reliability-based simulation methods for LSF_1, LSF_2 and LSF_3 is investigated. Since the vehicle velocity is usually one of the effective random variables on the probability of failure, the collision velocity is considered to be *20*, *40*, *60* and *80 Km/h* and Figure 1 showed the failure probability of mentioned frame for LSF_1. For example, by

reducing the vehicle velocity from *60* to *40 Km/h*, for the LSF_1, the probability of failure is reduced by *29%*, and by increasing its velocity from *60* to *80 Km/h*, respectively, increased probability of failure by *59%*. According to Figure 1, the results of the failure probability show that when the vehicle velocity reaches *80 Km/h*, the maximum failure probability for the limit state function *1*, is *0.52*. As a result, it is found that the conditions of the studied frame was more critical for the LSF_1 than for the other functions. Then the error rate of simulation based methods versus *MCS* method in different velocities of collision for LSF_1 is presented based on Figure 2 and the comparison of reliability index for three limit state functions are exhibited in different velocities using *CSS* method according to Figure 3.

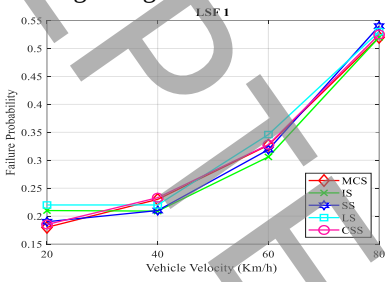

Figure 1. The failure probability comparison in different simulation methods for LSF_1

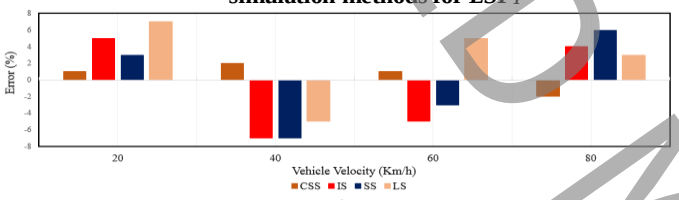

Figure 2. The error rate of simulation methods versus *MCS* method in different velocities of collision for LSF_1

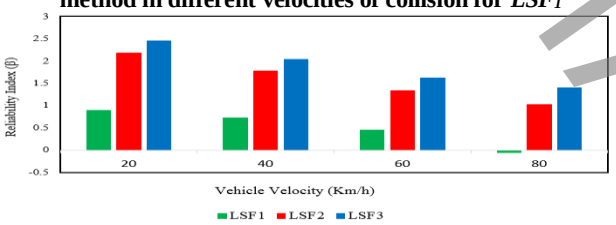

Figure 3. The comparison of reliability index for 3 limit state functions in different velocities using *CSS* method

4. Conclusion

In this study, the steel moment- resisting frame structure with *2*-story is modeled in *OpenSees* software, then, the sensitivity analysis of the desired random variables has been performed by *MCS* method. Finally, the limit state functions are presented based on the maximum permitted beam rotation of damaged bay and the failure probability and reliability index of the frame at different performance levels are calculated due to the light vehicle collision impact with different speeds such as *20*, *40*, *60* and *80 Km/h*. Then, probabilistic evaluation and reliability-based analysis have been performed using various simulation methods such as *MCS*, *IS*, *SS*, *LS* and *CSS*. By reviewing and comparing the results of probabilistic analyses, the new findings are mentioned in the following:

• The results of sensitivity analysis showed that the mass and velocity of the vehicle and the yield strength of the sections had the greatest effect and the Poisson ratio, the specific weight of the sections and the live load of the frame had the least effect on the failure probability.

• The results of probabilistic evaluation and reliability analysis showed that due to the low failure probability of frame due to vehicle impact, the *CSS* method with fewer samples and shorter running time, estimated accurately compared to *MCS* method.

• By calculating the probability of failure under different vehicle collision velocities for the three limit state functions, it is determined that with increasing velocity, the probability of failure increases and the reliability index decreases.

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