Fırat Üniversitesi Fen Bil. Dergisi
34(2), 129-137, 2022

Araştırma Makalesi

Standart Karayolu Köprüsünün Geometri ve Malzeme Yönünden Belirsizlikleri Dikkate Alarak Doğrusal Olmayan Statik Analizi

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(Geliş/Received: 08/08/2022; Kabul/Accepted: 15/08/2022)

Öz: Yapısal kapasitenin belirlenmesinde ilk ve en önemli aşamalardan biri malzeme dayanımlarının belirlenmesidir. Bu kısımda bir çok bilinmeyenin yer almasına karşılık, olasılıksal yaklaşımlardan faydalanılarak malzeme özellikleri deterministik olarak elde edilebilmektedir. Bununla birlikte geliştirilen olasılık modellerinde kullanılan yaklaşımlar ilave belirsizliklerin ortaya çıkmasına neden olmaktadır. Günümüzde gelişen bilişim ve bilgisayar teknolojileri yardımı ile malzeme yönünden belirsizliklerin yapısal tasarımlarda dikkate alınması mümkün hale gelmektedir. Bu nedenle geçmişte yönetmelikler tamamen deterministik yaklaşımları içerirken, günümüzde yarı-deterministik yaklaşımları içermekte ve tam olasılıksal yaklaşımların geliştirilebilmesi için çalışmalar yürütülmektedir. Bütün bunlar yapının performansının belirlenmesinde, yukarıda bahsi geçen belirsizliklerin dikkate alınmasını gerekli kılmaktadır. Ancak halen pratik ve güncel bir hesap yöntemi geliştirilebilmiş değildir. Bu çalışma kapsamında Türkiye karayolu hatlarında yer alan tipik bir köprü türü ele alınmış. Köprü ayağının moment-eğrilik ilişkisi malzeme belirsizlikleri dikkate alınarak modellenmiştir. Ayrıca kolon yükseklikleri ve köprü açıklıklarındaki belirsizlikler de Monte-Carlo yaklaşımı ile modellenmiş, köprünün yatay yük taşıma kapasitesinin belirlenebilmesi için artımsal statik itme analizi gerçekleştirilmiştir.

Anahtar kelimeler: Belirsizlikler, Monte-Carlo Yöntemi, Doğrusal Olmayan Statik Analiz, Moment-Eğrilik

Nonlinear Static Analysis of Ordinary Highway Bridges Considering Geometry and Material Uncertainties

Abstract: Material properties are an initial critical step to correctly determine the structure's capacities. Although there are many uncertainties, with the help of the probabilistic approach, the structural components' material strength was determined deterministically. The assumptions made to determine the material strengths generate additional uncertainties in determining the strength of the structures. Nowadays, developing computer technologies enable the determination of the strength capacities of structures with probabilistic approaches that consider these uncertainties in designing structural components. For this reason, while the approaches followed in the regulations included completely deterministic analyses in the past, quasi-statistical methods are used today, and studies are carried out to develop entirely statistical approaches. Therefore, to determine the structure's actual behavior, the uncertainties in the structural components should be taken into account. However, a practical and up-to-date approach has not been developed yet, and the existing methods impose an extensive analytical and computational burden. In this study, an ordinary single-column bridge in Türkiye was considered. Furthermore, the moment-curvature relationship of the pier was simulated considering material uncertainties. In addition, the differences in column heights and span lengths were modeled with the help of the Monte-Carlo simulation. Incremental static analyses were performed, and the lateral load-carrying capacities of the bridge were simulated.

Key words: Uncertainties, Monte-Carlo Simulation, Nonlinear Static Analysis, Moment-Curvature

1. Introduction

Turkey has three active fault lines, and nearly all of its land area is vulnerable to earthquakes. The transportation systems must continue to function even after significant earthquakes to allow people to reach the disaster zone sustainably, minimize economic losses, and not interrupt commercial activities. However, it is impossible to analyze all bridges, the most fragile components of existing transportation systems. For this reason, bridges were divided into specific groups by considering their structural behavior. It was accepted that the capacity analyses performed for these groups were valid for other bridges in the same group.

Another issue to be considered in determining the performance of bridges was structural and geometric uncertainties. Since the bridges in the defined group have different column heights and span distances, these

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differences should be considered in the analysis. Furthermore, the material attributes employed in the analytical approach are values that cannot be calculated deterministically and provide variable findings in each sample. However, with the help of experimental studies, it has been seen that these parameters can be represented using specific probabilistic models. It is critical to apply probabilistic techniques to predict the specific compressive and tensile strengths of materials used in bridge construction and elasticity modules, such as concrete and reinforcing steel. The Monte-Carlo simulation brings us essential amenities for modeling. It helps us to represent probabilistic models realistically. However, many models must be produced to represent the actual model, significantly increasing the analysis load. For this reason, different approaches such as Latin Hypercube Sampling and Important Sampling have been developed to reduce the number of samples and make analysis approaches applicable [1–4].

There are two indispensable factors in determining the horizontal displacement capacities of bridges. One of them is the determination of the nonlinear behavior of the bridge piers and their deformation capacity, and the other is the determination of the support responses. In modeling the behavior of the bridge piers, the acceptance of the behavior of plastic hinges comes to the fore. One of the most common methods for simulating the nonlinear behavior of piers is the plastic hinge exception. It is necessary to obtain the moment-curvature relationship of the bridge piers and determine their deformation capacity [5]. In addition, the pushover analysis has been widely used to determine the bridge's lateral load-carrying capacity. In this approach, the analysis should be performed by increasing the loads until a certain peak displacement is reached when the bridge has either static lateral loads or modal loads in a specified direction. Thus, the horizontal displacement capacity of the bridge in the relevant direction will be determined. The most important disadvantages of this approach are the difficulties in considering the high mode effects and the challenges in redistributing loads after the initial yield point is reached in the structural members.

Incremental Static analyses (Pushover) have been developed with the help of different approaches so that high mode effects can also be taken into account. A few of these approaches are the N2 methods, incremental static analysis, capacity spectrum methods, and adaptive capacity spectrum methods [6]. With the help of these approaches, it has become possible to determine the structural responses more realistically by considering the higher modal effects. However, since a significant part of the studies is focused on buildings, it is critical to determine the effectiveness of the developed approaches on bridges. In the studies carried out in this context, the effectiveness of the methods developed for certain bridges has been proven [7, 8]. However, the necessity of carrying out more comprehensive and extensive studies has been emphasized. Nowadays, with increasing interest, special studies such as the determination of the earthquake performance of steel bridges and the determination of the earthquake performance of high-speed train bridges are carried out with the help of pushover analysis [9–12]. Furthermore, the direction of the earthquake load affects the bridge's collapse mechanism and should also be considered in the pushover analysis. Therefore multidirectional pushover analysis was performed to determine the directional effects of earthquake loads [13]. Another exciting advancement is considering the near-fault ground motion to determine the bridge response. The rapture distance of the center of the earthquake and bridge affects the ground motions characteristic vitally there for considering the near-fault effect while pushover analysis has great importance [14].

Although dynamic analyses should be performed in the time domain to obtain more realistic results, static approaches can get results with the necessary convergence and reduce computational load and analysis costs [15, 16]. In addition; it also allows parametric studies that require a large number of analyses to be conducted.

Within the scope of this study, one of the ordinary bridge types designed as a Turkish highway bridge has been examined with the help of analytical models in which different uncertainties were taken into account. Different column heights and span distances for single-pier bridges with two spans were modeled using Monte-Carlo simulation, and material uncertainties were also considered. Pushover analyses were performed on the models developed using the OpenSees program. The horizontal displacement capacities of the bridge and the corresponding base shear forces were obtained by taking into account the uncertainties in the bridge. In addition, the moment-curvature relations for the bridge pier were also modeled with the help of Monte-Carlo simulation, and the yield curvatures, moment capacities, and rotational capacities of the piers were determined.

2. Bridge Modeling

Considering the ordinary highway bridges in Turkey, the essential parts of these bridges were built after the 1990s. The bridges are grouped into four different classes based on structural attributes [17]. Ordinary standard roadway bridges are defined by Caltrans (2006). Steel shim elastomeric bearings on the abutments and bending cap beams support the bridge superstructure. Elastomeric bearings as base isolators are commonly used to reduce the seismic load and are composed of steel plates, rubber pads, and steel core materials. The only force between the abutment-elastomeric bearing and the superstructure-elastomeric bearings is friction force. There are no connecting devices between the abutment and the superstructure and the elastomeric bearing. During a severe earthquake, the friction force can be exceeded, and the superstructure slides on the elastomeric bearing, and unseating occurs. The shear key was a fuse element designed to prevent the superstructure from dropping below the piers and sacrificed itself to protect the superstructure, piers, and abutments.

Ordinary roadway bridges in Turkey are composed of multi-span composite structures that include pre-stressed concrete girders and continuous cast-in-place reinforced concrete desks (See Figure 1). C40 and C25 concrete materials was used to build the girders and deck respectively, and S420 reinforcement steel was used for all reinforced members. Figure 2 shows the view of the typical single-column pier of the ordinary roadway bridge in Turkey.

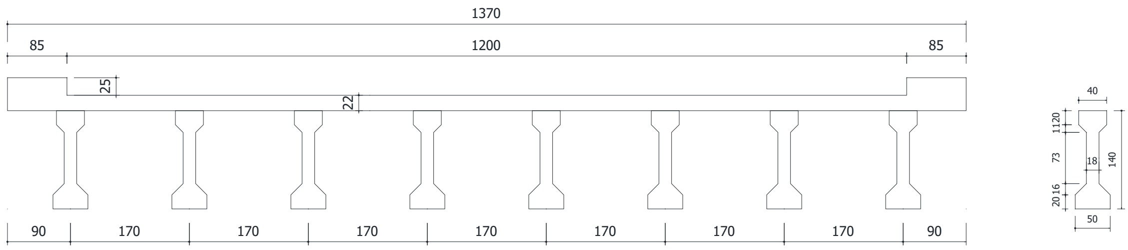

Figure 1 Typical shape of the superstructure of the ordinary bridges (All the dimensions are in cm)

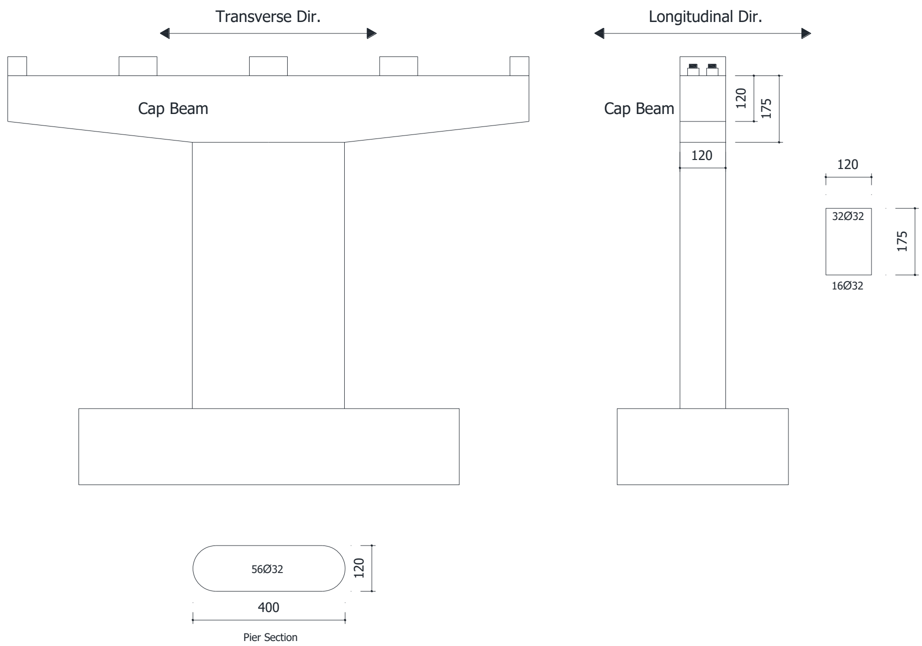

Figure 2 Typical view of the single column pier of the ordinary bridges

. A 3-D finite element model of the bridge was developed using OpenSees [18] software. The model took into account P- Δ with large displacements to determine the second-order effects on the piers. Concrete 02 materials were used to define both confined and unconfined concretes and ReinforcingSteel materials were used to describe the reinforcement steel materials. Expected values of the concrete and steel materials were considered in the analysis. The bridge's superstructure was assumed to be elastic under seismic excitation. Therefore elasticBeamColumn element modules were used to model the superstructure. dispBeamColumn elements were used to define the bridge's piers, and pier sections were defined using fiber section commands, including the torsional rigidity of the piers.

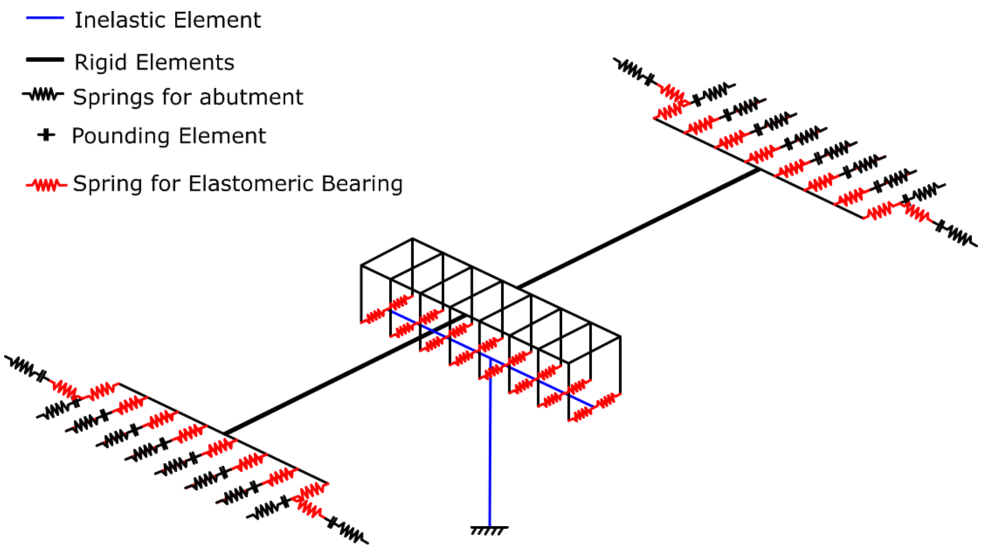

Figure 3 3-D analytical model of the bridges

The elastomer bearing transfers the lateral load with friction between the superstructure and the abutments. Because there was no connecting device, the lateral load-carrying capacities depended on the dynamic friction coefficient and the axial load acting on the systems. After the friction load exceeds the lateral load capacity, it remains constant. The friction coefficient is defined as 0.4 by Caltrans (2006). Elastomer bearings were modeled with ElasticPP material modeling. The elastomer bearing's initial rigidity was calculated using $K_{bearing} = \frac{G*A}{h_{nt}}$, where G is the shear modulus of the rubber pads, A is the area of the elastomer bearing, and h_{nt} is the total thickness of the rubber.

The bridge''s superstructure and substructure are not continuous in horizontal and vertical directions. The different behaviors of the two components cause an opening and closing of the expansion joint, which leads to a nonlinear and discontinuous effect on the bridge. When joints are closed, pounding occurs between adjacent bridge components, simulated by pounding elements. 50mm and 25mm gaps in longitudinal and transverse directions are modeled, respectively, with the initial stiffness and shear yielding capacity. ElasticPPGap materials were used to model the pounding elements. Moreover, the abutment and backfill soil models were created according to the [19] models.

3. Defining Material and Structural Uncertainties.

According to the inventory analysis conducted by [17], the bridge lengths are changed between 10 to 40 meters with mean 23.8m and a standard deviation of 6.1m and assumed to fit a normal distribution, moreover, the column height has the mean 6.73m long with standard deviation 2.04m and normally distributed. The concrete materials are defined as C25 material with expected compression stresses of 32.5MPa, and reinforcement steel has an expected yielding stress of 504 MPa. The uncertainties considered in the analytical models are presented in Table 1.

Table 1 Uncertainty distribution of the bridge characteristic models.

Modeling parameters	Probability Distribution	Mean	Covariance
Span Length	Normal	23.8	0.25
Column Height	Normal	6.73	0.3
Concrete Com. Strength	Normal	32.5	0.1
Rebar Yielding	Lognormal	504	0.05

Simulation process duplicates behavior of existing or designing system. It allows the engineer to experience the system's behavior either better understand the system or further management. The main advantages of simulation are understanding the essential component of the system, how they respond, and how they behave in the future. Properties of simulation outputs are determined by the input and transfer function. When the transfer function is simple, output properties can be calculated analytically. However, it is impossible in many cases because of different uncertainties and complex actions. In this case simulation, the technique gives a better solution with a reliable result depending on the number of simulations. When the number of simulations goes to infinity, the results coincide with exact, which is impossible to compute. Therefore, an adequate number of simulations should be determined in using simulation.

Monte Carlo simulation, which is the most commonly used effective tool, is used in this study with a hundred thousand samples. The simulation of the uncertainties of the bridge components and material properties was generated using normal distributions. Histograms of the distribution of the selected delays as shown in Figure 4.

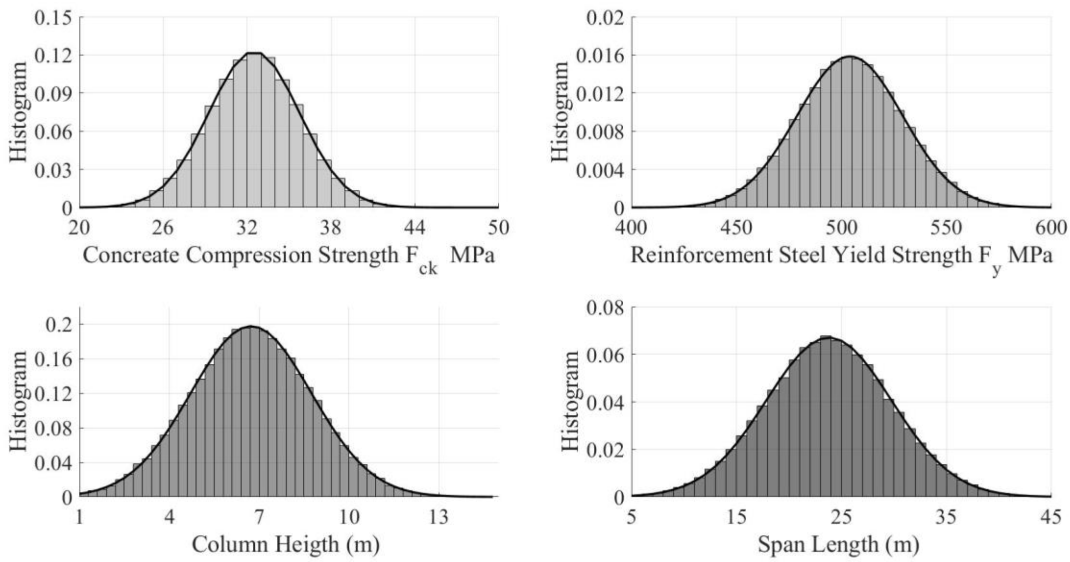

Figure 4 Histograms of the bridge components and materials distribution.

4. Discussion on Moment Curvature of the Bridge Piers.

The moment-curvature relationship of the bridge pier was obtained with the help of the OpenSees [18] program, taking into account the uncertainties modeled in the Monte Carlo simulation. Using the moment-curvature relations, the maximum moment capacity of the bridge pier and the angle of rotation at which yield occurs in the reinforcements in the bridge pier were simulated. Moreover, the curvature at which damage starts to occur and the non-linear deformation capacity of the bridge under lateral loads will be determined.

The expected value of the moment capacities of the column piers was determined as 4434kNm, and the standard deviation was determined as 171.7kNm. Figure 5 showed the histogram of moment capacities and was well-matched with normal and log-normal distribution curves. Considering that the normal distribution is used to model uncertainties in construction materials, it is seen that the moment capacity was well-matched with both the normal and log-normal distributions. The covariance value of the moment capacities of the column piers was determined as 0.038, which indicates that the distribution ratio of the moment capacities is low and the probability of obtaining a moment capacity close to the mean earthquake is high.

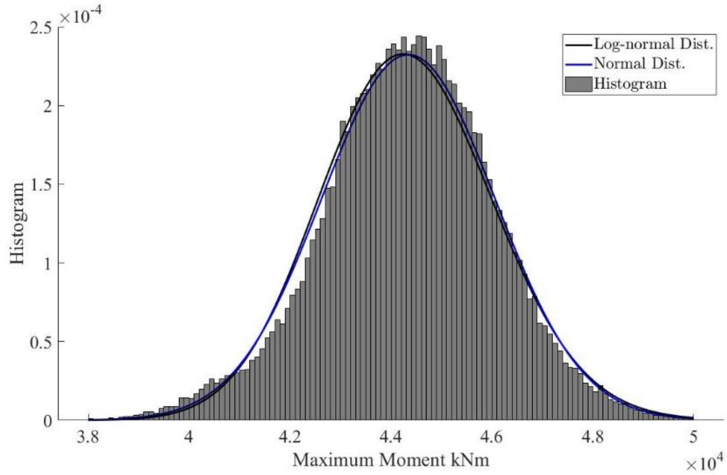

Figure 5 Bridge Piers Maximum moment distributions.

The rotation angle at which the first flow started in the piers was simulated considering the material uncertainties. Figure 6 presents the histogram of the obtained results. The expected values of curvature corresponding to the yield rotation were calculated as 0.0027 (1/m), and the standard deviation was calculated as 0.00014 (1/m). The covariance value was determined as 0.051. Figure 6 compares yield curvature values with normal and log-normal distributions. Consequently, it was discovered that the yield curvature closely matched the normal distribution.

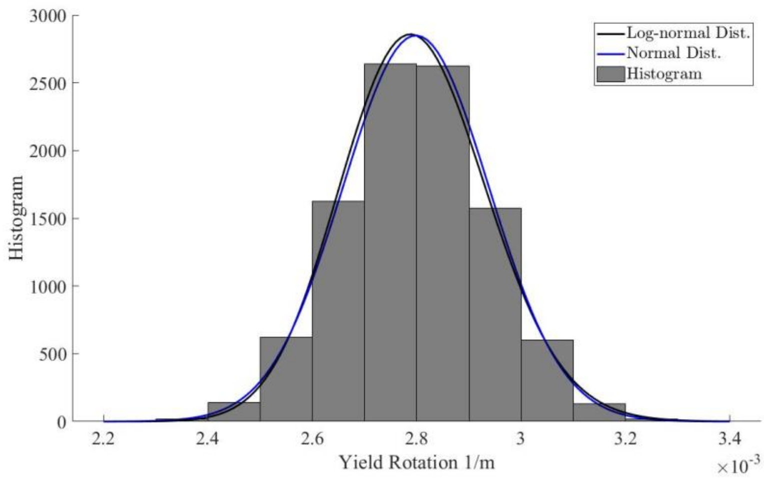

Figure 6 Bridge Piers Yield Rotation Curvature distributions

Hundred-thousand simulations were used to determine the structural uncertainties. The moment capacities obtained from the modeling were expected to converge to a specific mean and standard deviation value. Although the essential advantage of the MSC approach is that it allows all uncertainties to be taken into account as they were, it is also necessary to determine whether a sufficiently large number of simulations has been reached. Furthermore, the findings produced in models run with low simulation numbers differ significantly from the actual values. The variations in the averages of the computed moment capacity values according to the simulation numbers are presented in Figure 7. The number of reasonable simulations within the scope of this study was calculated. Accordingly, after ten-thousand simulations, the average values converged at a specific moment capacity. Therefore, it was seen that realistic results could be obtained if ten thousand or more simulations were performed to determine the moment capacities of the investigated column piers.

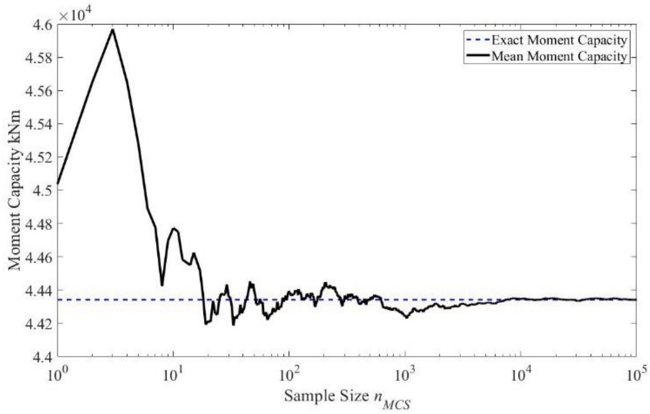

Figure 7 Distribution of the Sample Sizes and mean moment capacities.

5. Discussion on the Bridge capacity

Using the non-linear model of the bridge and considering the uncertainties in concrete compressive strength, reinforcement yield strength, column heights, and bridge span lengths, the bridge capacity was determined with the help of ten-thousand samples. With the use of incremental static analysis on the models, the horizontal load-carrying capabilities of the bridge were tried to be determined. Figure 8 shows the maximum, mean, and minimum base shear forces determined from the analysis. As a result of the study, it was seen that there were significant differences in the base shear forces. The base shear forces were significantly affected by the uncertainties in the material models and the geometric uncertainties, such as the height of the bridge piers and the bridge's width.

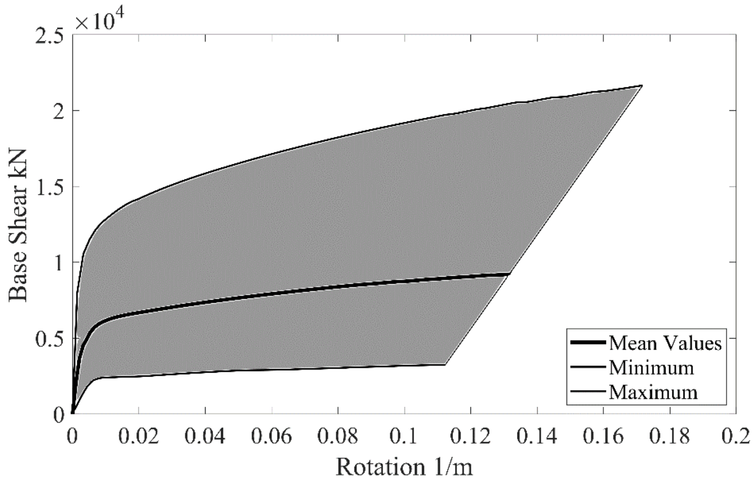

Figure 8 Pushover diagrams of the bridge based on Base Shear and Piers rotations.

6. Conclusion.

Bridges "under natural disasters" are the most vulnerable components of the transportation networks. For this reason, it is essential to determine the structural performance of bridges. In this context, dividing the existing bridges into specific groups and determining the horizontal load-carrying capacities of these groups provides general and practical information about the capacities of the bridges. This work investigated the horizontal load-carrying capability of an ordinary highway bridge in Türkiye regarding material and geometry uncertainties.

- The concrete's compressive strength and the reinforcing steel's tensile strength were considered material uncertainties in the bridge design. The Monte-Carlo method simulated the predicted concrete compressive strength and steel tensile strength with a normal distribution.

- The moment-curvature relationship of the piers modeled with the help of fiber elements was obtained by considering non-linear material prototypes and uncertainties in material strength.

- Moment capacities of the piers have 4434 kNm mean, and 171.7 kNm standard deviation and well fit with the normal distribution.

- When the rotational curvatures of Piers elements were examined, it was determined that yielding started at an average of 0.0027 (1/m) curvature.

- To examine the effectiveness of the number of samples involved in the simulation, a sensitivity analysis is performed. After 10^4 samples, the moment capacity approximated the average value.

- The horizontal load-carrying capacity of the bridge as a system and the corresponding rotational values were obtained. The ones corresponding to the average, maximum, and minimum base shear forces were plotted graphically.

Refereneces

[1] Biondini F. Use of Simulation in Structural Reliability. Struct. Congr. 2008, 2008.
[2] Melchers RE. Importance Sampling in Structural Systems. Struct Saf 1989;6:3–10.
[3] Infanger G. Monte Carlo (Importance) Sampling Within a Benders Decomposition Algorithm for Stochastic Linear Programs. Ann Oper Res 1992;39:69–95.
[4] Oh M, Berger JO. Adaptive importance sampling in monte carlo integration. J Statictical Comput Simul 1992;41:143–68. doi:10.1080/00949659208810398.
[5] Yilmaz MF. Reliability analysis of Bridge with Monte-Carlo Simulation. Int. Congr. Phenomenol. Asp. Civ. Eng., Erzurum/ Turkey: PACE 2021; 2021, p. 1–6.
[6] Perdomo C, Monteiro R, Sucuoğlu H. Generalized force vectors for multi-mode pushover analysis of bridges. Bull Earthq Eng 2017;15:5247–80. doi:10.1007/s10518-017-0179-6.
[7] Pinho R, Casarotti C, Antoniou S. A comparison of single-run pushover analysis techniques for seismic assessment of bridges. Earthq Eng Struct Dyn 2007;36:1347–62. doi:10.1002/eqe.684.
[8] Paraskeva TS, Kappos AJ. Further development of a multimodal pushover analysis procedure for seismic assessment of bridges. Earthq Eng Struct Dyn 2009;39:211–22. doi:10.1002/eqe.947.
[9] Lu Z, Ge H, Usami T. Applicability of pushover analysis-based seismic performance evaluation procedure for steel arch bridges. Eng Struct 2004;26:1957–77. doi:10.1016/j.engstruct.2004.07.013.
[10] Bignell JL, LaFave JM, Hawkins NM. Seismic vulnerability assessment of wall pier supported highway bridges using nonlinear pushover analyses. Eng Struct 2005;27:2044–63. doi:10.1016/j.engstruct.2005.06.015.
[11] Zordan T, Briseghella Bruno B, Lan C. Parametric and pushover analyses on integral abutment bridge. Eng Struct 2011;33:502–15. doi:10.1016/j.engstruct.2010.11.009.
[12] Guo W, Hu Y, Liu H, Bu D. Seismic performance evaluation of typical piers of China's high-speed railway bridge line using pushover analysis. Math Probl Eng 2019;2019. doi:10.1155/2019/9514769.
[13] Araújo M, Marques M, Delgado R. Multidirectional pushover analysis for seismic assessment of irregular-in-plan bridges. Eng Struct 2014;79:375–89. doi:10.1016/j.engstruct.2014.08.032.
[14] Bergami AV, Fiorentino G, Lavorato D, Briseghella B, Nuti C. Application of the incremental modal pushover analysis to bridges subjected to near-fault ground motions. Appl Sci 2020;10:1–19. doi:10.3390/app10196738.
[15] Bergami AV, Nuti C, Lavorato D, Fiorentino G, Briseghella B. Incremental Modal Pushover Analysis for Bridges. Appl Sci 2020;10:1–24.
[16] Yılmaz MF, Aydın AC. Assessment of an old roadway bridge under static and seismic loading conditions. Chall J Struct Mech 2021;7:107. doi:10.20528/cjsmec.2021.02.006.

[17] Avşar Ö, Yakut A, Caner A. Analytical Fragility Curves for Ordinary Highway Bridges in Turkey. Earthq Spectra 2011;27:971–96. doi:10.1193/1.3651349.
[18] PEER. Open System for Earthquake Engineering Simulation (OpenSees) 2005.
[19] Caltrans. Seismic Design Criteria. Sacramento, CA.: 2006.