Universidad Autónoma Del Estado De México

Facultad de Ingeniería

Análisis de confiabilidad en columnas de puentes vehiculares de concreto reforzado utilizando redes Bayesianas no paramétricas: ejemplo de aplicación.

TESIS POR ARTÍCULO ESPECIALIZADO

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RESÚMEN

En la industria de los puentes, las tendencias actuales del tráfico han aumentado la probabilidad de tener la presencia simultánea de cargas vivas extremas y eventos sísmicos. Hasta la fecha, su interacción concurrente apenas ha sido estudiada sistemáticamente. Los estudios predominantes han investigado la existencia aislada de cargas vivas o acciones sísmicas.

Se ha propuesto una Red Bayesiana no paramétrica (BN) dirigida a evaluar la probabilidad condicional de falla para una columna de un puente de concreto reforzado, sujeto simultáneamente a las acciones mencionadas anteriormente. Partiendo de datos reales de una estructura ubicada en el Estado de México, se desarrolló un modelo de simulación de Monte Carlo. Esto llevó a la construcción de una BN con 17 variables.

El conjunto de variables incluidas en el modelo se puede clasificar en tres grupos: cargas activas, resistencias de los materiales y elementos mecánicos de la estructura. Es posible recopilar información in situ (por ejemplo, datos de peso en movimiento y mediciones de martillo Schmidt), que pueden incluirse en la red, lo que lleva a una probabilidad actualizada de falla. Además, este marco también sirve como una herramienta cuantitativa para la evaluación de la confiabilidad de columnas de puentes.

Los resultados del modelo teórico confirmaron que la probabilidad de falla de la columna puente estaba dentro del rango esperado e informado en la literatura. Esto refleja no solo la idoneidad de su diseño sino también la capacidad de la BN propuesta para el análisis de confiabilidad.

ABSTRACT

In the bridge industry, current traffic trends have increased the likelihood of having the simultaneous presence of both extreme live loads and earthquake events. To date, their concurrent interaction has scarcely been systematically studied. Prevailing studies have investigated the isolated existence of either live loads or seismic actions.

In an effort to fill this gap in the literature, a non-parametric Bayesian Network (BN) has been proposed. It is aimed at evaluating the conditional probability of failure for a reinforced concrete bridge column, subject simultaneously to the actions mentioned above. Based on actual data from a structure located in the State of Mexico, a Monte Carlo Simulation model was developed. This led to the construction of a BN with 17 variables.

The set of variables included in the model can be categorized into three groups: acting loads, materials resistances and structure force-displacement behavior. Practitioners are then provided with a tool for unspecialized labor force to gather information in-situ (e.g. Weight-In-Motion data and Schmidt hammer measurements), which can be included in the network, leading to an updated probability of failure. Moreover, this framework also serves as a quantitative tool for bridge column reliability assessments.

Results from the theoretical model confirmed that the bridge column probability of failure was within the expected range reported in the literature. This reflects not only the appropriateness of its design but also the suitability of the proposed BN for reliability analysis.

INTRODUCCIÓN

Los puentes son estructuras de alto impacto que están amenazadas por diferentes peligros, como terremotos y cargas de tráfico elevadas. La posibilidad de tener la presencia combinada de cargas vivas y eventos sísmicos no es remota (Wibowo2013). Estos eventos pueden conducir a un daño en el puente que a su vez puede provocar consecuencias negativas en los sistemas de transporte.

Las cargas de vehículos que excedan los límites legales de peso causan serias amenazas a las operaciones de transporte por carretera. Los modelos de carga viva de muchos reglamentos son solo teóricos, y comúnmente se calibran para reproducir un efecto de la carga y no la magnitud real en sí misma (Ghosh2014). Además, la frecuente ocurrencia de terremotos podría causar daños y acelerar aún más el deterioro de los puentes, lo que podría conducir eventualmente a una falla catastrófica. (Tan2017)

Para evaluar los impactos del escenario descrito anteriormente, se realizará un análisis de confiabilidad. Para hacerlo, es necesario reunir medidas consistentes de seguridad en eventos inciertos. Entre las herramientas de confiabilidad disponibles, las Redes Bayesianas (BN) ofrecen la oportunidad de cumplir estos requisitos, ya que representan problemas de probabilidad multidimensionales con un número reducido de parámetros. Además, las BN se pueden actualizar cuando haya nuevos datos disponibles.

El propósito de este trabajo de investigación es estimar la probabilidad condicional de falla de la columna de concreto reforzado de un puente a través de una BN. Para este fin, las variables consideradas en el estudio son: intensidad sísmica, cargas de tráfico y propiedades de los materiales.

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ANEXO

ACUSE DE RECIBO (MANUSCRIPT DETAILS-SUBMISSION FILES)

PARTE 1. PROTOCOLO DE TESIS

Contenido

1. Problema de estudio.

La inversión en infraestructura resulta indispensable para el desarrollo económico y social de un país, ya que eleva la competitividad de la economía. Además, estimula a la industria de la construcción y a los sectores que dependen de ella.

En México, la inversión en infraestructura ha sido un tema estratégico y prioritario porque representa el medio para generar desarrollo y crecimiento económico, y es una pieza clave para incrementar la competitividad [1]. En este tenor uno de los sectores prioritarios es el de comunicaciones y transportes.

La infraestructura carretera incide de forma determinante en el empleo y la conectividad y es siempre una buena inversión. La construcción de carreteras promueve la reactivación de la industria de la construcción y con ello genera un mayor dinamismo en la economía [2]. Los puentes como parte de la infraestructura carretera a lo largo de su existencia, han traído como beneficio la comunicación para las ciudades y los diferentes asentamientos humanos. Estos también, se emplean para salvar obstáculos que pueden ir desde barrancos hasta ríos.

La falla de un puente puede deberse a distintos factores como: lluvias extraordinarias, sismos, mantenimiento esporádico, plasticidad, fatiga, fractura, desplazamientos y corrosión, que generalmente producen el mal funcionamiento de los elementos estructurales, provocando pérdidas importantes [3].

Hoy en día es más probable que los puentes experimenten la presencia de vehículos pesados mientras se presenta un movimiento sísmico, debido al crecimiento poblacional el cual ha dado lugar a un aumento del número de vehículos y a la necesidad de mover cargas entre ciudades [4].

En la seguridad estructural, se comparan los efectos de las cargas con las resistencias. Estas variables no se pueden asignar con un valor único, su variación es mejor tratada con modelos probabilísticos.

Las redes bayesianas (BN) son de gran importancia en problemas complejos y de gran incertidumbre en disciplinas como ingeniería y ciencias naturales.

El enfoque en este trabajo es usar redes bayesianas para estimar la probabilidad de falla de una columna de concreto reforzad en un puente vehicular. Las incertidumbres que influenciaras la BN son: intensidad sísmica aleatoria, cargas de tráfico pesado al aleatorias y propiedades de los materiales al aleatorias, modelando el puente con un modelo de simplificado para obtener el comportamiento estructural y con nueva información, se pueda realizar una actualización de los resultados. Esto facilita la toma de decisiones en la etapa de evaluación de la confiabilidad, durante la planificación del diseño y mantenimiento.

2. Revisión bibliográfica.

Uno de los primeros estudios estadísticos sobre fallas de puentes lo presentó Smith en 1976, quien analizó 143 puentes en todo el mundo, llegando a la conclusión de que la causa principal por la que colapsaban la mayoría de los puentes se debía al tránsito de avenidas (teniendo como problema principal la socavación); en menor medida se detectaron los materiales, los sismos, la construcción defectuosa y las sobrecargas e impacto de embarcaciones. Adicionalmente, en casos menos frecuentes se encontraban las fallas asociadas a un diseño inapropiado, viento, fatiga y corrosión [5].

En la década de 1990 algunos de los sismos más fuertes en Japón y en Estados Unidos causaron docenas de colapsos en puentes demostrando así la deficiencia existente en los códigos de diseño. De acuerdo con George C. Lee [6] las columnas son la parte más vital en la resistencia de un puente en contra de un sismo, y 67% de las fallas fueron causadas por alguna debilidad asociada a esos elementos estructurales.

Cuando se habla de seguridad estructural, la resistencia es comparada con los efectos de la carga experimentados por la estructura debido a la acción de causas externas. Dada la variedad de incertidumbres involucradas, a estas variables (resistencia y carga) no se les puede asignar un valor único, y su variación se trata mejor utilizando modelos probabilísticos.

La resistencia estructural depende principalmente de las propiedades del material. Estas propiedades han sido especificadas como valores característicos, es decir, estas son solo una parte de la función de densidad de probabilidad de la población de la variable, pero pueden ser más altas en realidad. Al incluir los resultados de pruebas realizadas *in situ* se puede lograr un mayor grado de precisión y, por lo tanto, se puede mejorar la calidad en la evaluación de la seguridad [7]. Las pruebas *in situ* pueden aplicarse durante la operación de las estructuras y es una manera efectiva de evaluar las propiedades estructurales actuales y detectar los daños. También pueden servir como una herramienta para la detección continua [8].

Actualmente la evaluación de la seguridad de los puentes de concreto reforzado se realiza principalmente mediante inspecciones visuales. Sin embargo, las inspecciones visuales tienen varias limitaciones dado que los datos obtenidos son subjetivos ya que dependen de la experiencia del inspector.

La estimación de la condición de los materiales de construcción es crítica cuando se reevalúan las estructuras existentes, ya que el envejecimiento del material puede resultar en pérdida de rendimiento, degradación de la seguridad y costos de mantenimiento [9]. Por estas razones, la obtención de datos mediante pruebas *in situ* se ha vuelto una importante herramienta para evaluar el estado de los puentes de concreto reforzado existentes.

En cuanto a las cargas, los modelos de los códigos de construcción son generalmente precisos, pero pueden actualizarse cuando la situación local parece ser muy diferente de la situación extrema en la que se basan los modelos de carga respectivos. Las variaciones tanto en las cargas como en las resistencias motivan el análisis de incertidumbre y confiabilidad en las obras.

De acuerdo con la Norma ISO 31000 [10] el riesgo es el efecto de la incertidumbre sobre los objetivos, siendo un efecto una desviación de lo esperado ya sean positivos y/o negativos, el cual se caracteriza a menudo por referencia a los eventos potenciales y consecuencias.

En el ámbito de la Ingeniería Civil, el riesgo debe ser entendido como las consecuencias esperadas asociadas con una actividad dada. Las consecuencias son medidas en términos monetarios, pérdida de vidas humanas, etc. [11]

Considerando una actividad con un solo evento y concecuencias potenciales C, el riesgo R es la probabilidad de que el evento ocurra P multiplicado por la consecuencia de dicho evento ocurrido:

$$R = P * C$$

De acuerdo con Wesley Cook [12] en una muestra que consiste de 103 fallas de puentes desde 1987 a 2011 la tasa de falla esperada de un puente se encuentra en un intervalo de 1/6900 (0.000145) y 1/2700 (0.00037) anualmente. Con base en estos antecedentes, se pretende demostrar la siguiente hipótesis.

3. Hipótesis.

La probabilidad de falla de una columna de concreto reforzado expuesta a carga viva máxima y sismo simultáneamente es de 0.0001

4. Objetivo.

Evaluar la probabilidad de falla de una columna de concreto reforzado sujeta simultáneamente a grades cargas vehiculare y sismos fuertes. Caracterizando la parte de resistencia de materiales usando pruebas *in situ* que determinen las propiedades índices del elemento en un entorno donde adicionando la información obtenida se actualice la distribución de la resistencia por medio de redes bayesianas.

4.1 Alcance

El trabajo solo abarca las variables de aceleración máxima del suelo, carga viva, así como la resistencia del material en columnas de concreto reforzado tales como resistencia a compresión, módulo de elasticidad, resistencia a la tensión del acero de refuerzo y fluencia del acero de refuerzo, se consideraran fallas debidas a flexo compresión, cortante y excedencia de la distorsión máxima permitida de la columna, no se considerará cuestiones como: efectos viento, fatiga, cuestiones de mantenimiento, etc.

En el modelo simplificado de análisis se considerarán materiales linealmente elásticos, la parte baja de la columna empotrada, presencia simultanea de dos vehículos en diferentes posiciones, análisis no lineal “Time History”. No se considerará la interacción suelo estructura, el cambio de rigidez en la sección agrietada.

5. Metodología propuesta.

a) Revisión bibliográfica.

b) Selección de caso de estudio con base en la disponibilidad de datos existentes de pruebas de materiales durante su construcción[1]
c) Definición de secciones transversales, propiedades de los materiales, cargas verticales y cargas laterales.
d) Realizar el análisis estructural no lineal con combinaciones de cargas aleatorias mediante el programa SAP 2000 v.14.
e) Obtención de elementos mecánicos del elemento estructural para cada combinación de cargas.

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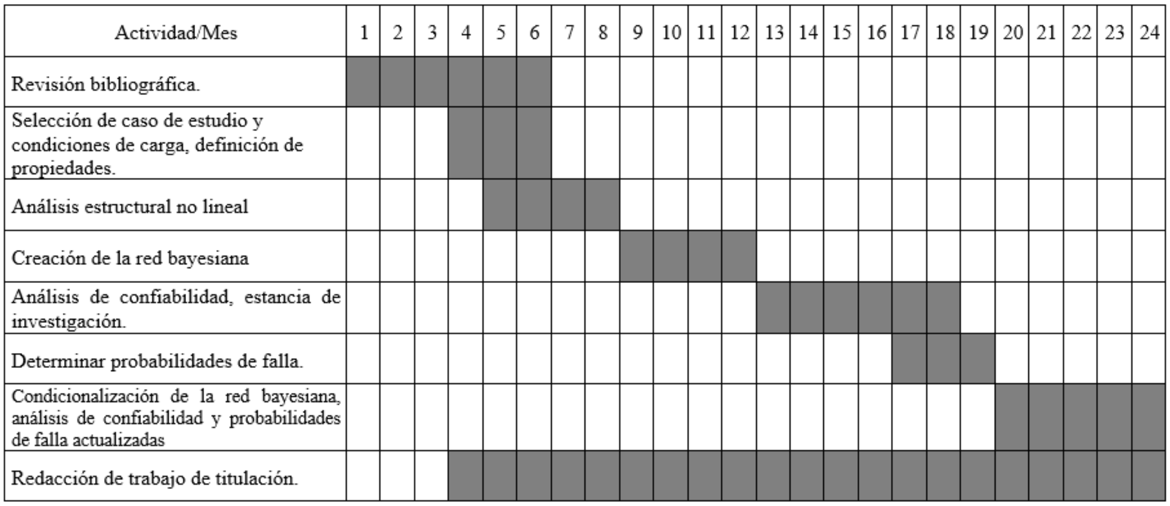
[1] El autor ha trabajado en el Laboratorio de Materiales de la FI-UAEMex desde 2013, y puede acceder a la información de pruebas de resistencia con propósitos académicos.

f) Creación de la red bayesiana con las variables de incertidumbre de interés, así como con los elementos mecánicos y desplazamientos de interés.
g) Análisis de confiabilidad mediante una función de estado límite para cada condición de falla y para cada combinación.
h) Determinar probabilidades de falla del elemento de estudio.
i) Condicionalización de la red bayesiana
j) Análisis de confiabilidad actualizado mediante la función de estado límite.
k) Determinar probabilidades de falla actualizadas del elemento de estudio.

6. Cronograma



Actividad/Mes	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
Revisión bibliográfica.	■	■	■	■	■	■																		
Selección de caso de estudio y condiciones de carga, definición de propiedades.				■	■	■																		
Análisis estructural no lineal					■	■	■	■																
Creación de la red bayesiana									■	■	■	■												
Análisis de confiabilidad, estancia de investigación.													■	■	■	■	■	■						
Determinar probabilidades de falla.																	■	■	■					
Condicionalización de la red bayesiana, análisis de confiabilidad y probabilidades de falla actualizadas																				■	■	■	■	■
Redacción de trabajo de titulación.				■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■

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PARTE 2. ARTÍCULO DE INVESTIGACIÓN

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Reliability analysis of reinforced concrete vehicle bridges columns using non-parametric Bayesian networks[☆]

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Abstract

In the bridge industry, current traffic trends have increased the likelihood of having the simultaneous presence of both extreme live loads and earthquake events. To date, their concurrent interaction has scarcely been systematically studied. Prevailing studies have investigated the isolated existence of either live loads or seismic actions.

In an effort to fill this gap in the literature, a non-parametric Bayesian Network (BN) has been proposed. It is aimed at evaluating the conditional probability of failure for a reinforced concrete bridge column, subject simultaneously to the actions mentioned above. Based on actual data from a structure located in the State of Mexico, a Monte Carlo Simulation model was developed. This led to the construction of a BN with 17 variables.

The set of variables included in the model can be categorized into three groups: acting loads, materials resistances and structure force-displacement behavior. Practitioners are then provided with a tool for unspecialized labor force to gather information in-situ (e.g. Weight-In-Motion data and Schmidt hammer measurements), which can be included in the network, leading to an updated probability of failure. Moreover, this framework also serves as a quantitative tool for bridge column reliability assessments.

[☆] This document is a collaborative effort.

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Results from the theoretical model confirmed that the bridge column probability of failure was within the expected range reported in the literature. This reflects not only the appropriateness of its design but also the suitability of the proposed BN for reliability analysis.

Keywords: `Bridge`, Reliability, Reinforced concrete columns, Bayesian Networks
2010 MSC: 00-01, 99-00

1. Introduction.

Bridges are high impact engineering structures which are menaced by different hazards such as earthquakes and high traffic loads. Then the possibility of having the combined presence of live loads and seismic events is not remote [1]. These events may lead to a bridge damage which in turn may provoke negative consequences in the transportation systems.

Vehicle loads exceeding the legal weight limits, cause serious threats to road transport operations. Live-load models of many codes of practice are theoretical only, and are commonly calibrated for reproducing a load effect and not the actual magnitude of the load itself [2]. Additionally the frequent occurrence of earthquakes could lead to damage and would further accelerate the deterioration of bridges, which might conduce eventually to a catastrophic failure. [3].

In order to assess the impacts of the previously described scenario, reliability analyses are performed. To do so, it is necessary to gather consistent measures of safety under uncertain events. Among the available reliability tools, Bayesian Notworks (BN's) offer the opportunity to fulfill these requirements, because they represent multidimensional probability problems with a reduced number of parameters. In addition, BN's can be updated when new data becomes available.

The purpose of this piece of research is to estimate the bridge reinforced concrete column conditional Probability of Failure POF through a BN. To this end, the variables considered in the study are: seismic intensity, traffic loads and materials properties.

In the subsequent sections, a typical Mexican bridge will be firstly presented. Then, the failure mechanisms of reinforced concrete (RC) columns will be explained. Next, the theory behind BNs will be discussed in combination with the variables considered in the research. To complete the discussion, some limit state functions will be introduced. Then, the resultant BN and its main features will be explained, along with its use in the above mentioned structure. The main findings of the study will then be discussed. Finally, the conclusions of the investigation will be drawn.

2. Mexican bridge

The structural element under analysis is the central bent column of a bridge built in 2014, with two lanes and located in the state of Mexico. The bridge has eight 35.0 m spans, each of which has six concrete box girders. Their ends rest on bents composed by 2 circular RC columns, with a diameter of 1.40 m and a square pier cap of 1.4 m. The length and cross section of the interest column are depicted in Figure 1. In terms of its reinforcement features, 37 longitudinal steel bars with a diameter of 25.4 mm, and spiral transversal reinforced with 12.7 mm steel bar (1 turn every 10 cm) are considered.

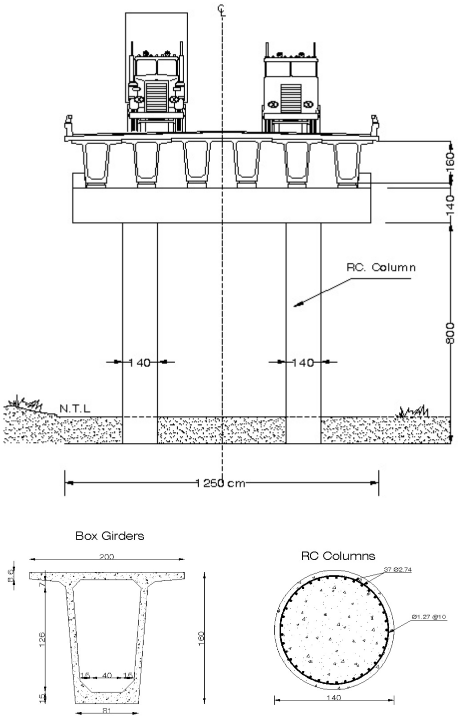


Figure 1: Plane, vertical view and details of the structure under analysis [cm].

The bridge under study was chosen because it represents 73.1% of the structures built in the state of Mexico [4] over the last four decades. Moreover, it is situated in a seismic zone with frequent annual activity [5]. In parallel, considerable traffic loads use the structure on a daily basis [6]. Consequently, it fulfilled the established criteria to carry out the required analysis. Prior to explaining the construction of the BN, it is important to understand the RC column failure modes.

3. Reinforced concrete columns failures modes

There are different failure mechanisms of RC columns, e.g. elastic instability and pure compression. The recorded data of damaged columns during past strong motion events revealed two main failure conditions: flexural and shear [7]. As will be discussed later, these two have been chosen to propose the limit state functions to perform a reliability analysis. Moreover, to include a service limit state evaluation, the drift exceed likelihood of the element will also be assessed. Eventhough a comprehensive description of the failure modes can be found elsewhere [8], next some highlights will be presented.

3.1. Combined axial and flexural strength

Interaction diagrams are a visual representation of the combined loads, usually bending moment (M) and axial load (P), that will cause the RC column to fail. These diagrams are created assuming a series of strain distributions and computing the corresponding values of P and M [9]. Following the steps detailed in [10], the nominal axial load (P) and the bending moment capacity (M) about the assumed neutral axis were estimated the for element of interest.

3.2. Shear strength

The shear strength (V_U) of RC members is affected by a number of parameters: applied shear stress level, level of imposed ductility, level of axial compression force, aspect ratio, transverse steel ratio, and longitudinal steel ratio [11]. V_U for a circular cross section in combined bending and compression stress regime adopted in the Mexican code NTC RCDF[12] is given as follows:

$$V_U = V_{CR} + V_{SR} \tag{1}$$

Where V_{CR} is the contribution of the concrete to shear strength, and V_{SR} is the contribution of the shear reinforcement.

3.3. Drift

Since this research is aimed at obtaining the POF of the mentioned limit states, the resistance component in this case will be the permissible drift. Basically the drift (γ) is a representative measure of a structural system affected by seismic forces, calculated as:

$$\gamma = \frac{U}{H} \tag{2}$$

Where H is the height of the column and U is the lateral displacement.

Based on the recommendations given in [13], a response modification factor (R=3) for vertical RC vertical piles was selected. According to the Mexican procedure NTC-RSEE [14], the corresponding maximum drift value is γ_{max}=0.02. Having highlighted these points, in the next section the theory behind BN's will be briefly presented.

4. Non-Parametric Bayesian Networks

BN's are directed acyclic graphs, consisting of nodes and arcs. The first represent uncertain or random variables which can be either continuous, discrete or functional. And the latter represent the causal or influential links between these uncertain variables [15].

The theory of non-parametric BN's is built around bivariate copulas. They are a class of bivariate distributions whose marginals are uniform on the uniform interval [16]. The use of the normal copula reduces and simplifies the joint distribution sampling, when dealing with high dimensional continuous BN's. Correlation = 0 implies independence, for the normal copula. The relationship between the rank correlation of the normal variables r, and the product-moment correlation of the normal variables ρ is given by [17]:

$$\rho(X,Y) = 2sin\left(\frac{\pi}{6}r(X,Y)\right) \tag{3}$$

When building a non-parametric BN, there are two properties that should be validated: (i) that the data has a normal copula and (ii) that the BN represents enough dependence. To do so, the d-calibration score is computed. It uses the following of three variants.

- ERC: empirical rank correlation matrix.
- NRC: empirical rank correlation matrix under the assumption of the normal copula.
- BNRC: Bayesian network rank correlation matrix.

The score is 1 if the matrices are equal, and 0 if one matrix contains a pair of variables perfectly correlated. The score will be small as the matrices differ from each other element-wise [18]. The d-calibration score is given by:

$$d(\Sigma_1,\Sigma_2) = 1 - \sqrt{1-\eta(\Sigma_1,\Sigma_2)} \tag{4}$$

$$\eta(\Sigma_1,\Sigma_2) = \frac{det(\Sigma_1)^{1/4}det(\Sigma_2)^{1/4}}{det\left(\frac{1}{2}\Sigma_1+\frac{1}{2}\Sigma_2\right)^{1/2}} \tag{5}$$

Where Σ_1 and Σ_2 are the correlation matrices of interest. More details for non parametric BN's can be consulted in [19]. Now that a typical Mexican bridge has been presented, the failure modes of the RC column discussed, and the BN theory briefly described, the steps for building the network of interest will be exposed.

5. Framework for building the BN

The requirements of the BN have been divided into three categories: traffic loads, ground motion and bridge information. The first refers to the position of the two trucks in the bridge relative to the beginning of the structure, the number of axles per lane, the gross weight per vehicle and the weight per lane. The second considers the seismic accelerograms used in the study with their corresponding Peak Ground Accelerations (PGAs). The third is related to resistance material properties (concrete and reinforcement steel) and the Finite Element Model (FEM) of the bridge.

It should be noted, that the list of variables selected is not exhaustive, it only considered those that take part in the initial stages of the phenomena. The main selection criteria used was the availability of data by means of either experiments, experts or simulation. Figure 2 shows the whole framework for building the BN, based on the model described in [2].

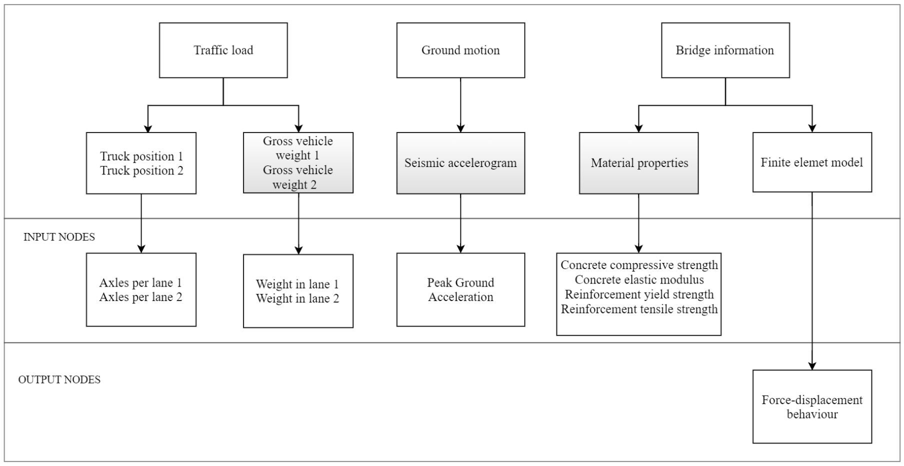


Figure 2: Framework for the joint live load and earthquake loads

To operationalize the process, a computer script was written in MATLAB, aimed at controlling SAP2000 through an Application Program Interface (API). The algorithm used to run the exercise included the following phases:

1. Based on the principles of Monte Carlo Simulation (MCS), random numbers are generated for each of the input variables (see input nodes in Figure 2).

2. The MATLAB script is executed with the random data.

3. The corresponding output variables are obtained by means of SAP2000.

4. The processes is repeated.

Here, given the available computational resources and time to carry out the research, 3500 realizations have been performed. It is important to note that the resultant imprecision level is 0.010 for a 99% confidence interval [20]. With these ideas in mind, now the categories within the framework will be detailed.

5.1. Traffic loads

According to the Mexican standard NOM-012-SCT-2-2014 [21] there are three main types of design vehicles with a maximum weight of 740.4 kN. However, empirical evidence has revealed that it is lower than the actual Mexican highway traffic loads. Garcia-Soto [22] reported a maximum gross vehicular weight of 1307.7 kN in a main highway located in central Mexico, i.e. 1.75 times the maximum allowed within the standard.

In terms of the vehicle masses, the weight in motion (WIM) system was designed for quantifying axle loads, vehicular weights, inter axial separations, vehicle lengths and speeds [23]. It represents a good alternative for knowing the traffic flow characteristics in the bridge under analysis. However, evidence about the existence of WIM in Mexico is scarce [22].

As a consequence, and based on the experience of one of the authors [23], data from the Dutch WIM was used to carry out the simulation exercise presented in this paper. It should be noted here, that the aim of the research is to establish a theoretical methodology for reliability analysis of RC bridge columns. In a practical evaluation, actual data form the structure under analysis should be employed. Having clarified the point, Figure 3 shows the total weight per lane considered for the case study.

As can be seen, the corresponding empirical distribution has a mean of 545 kN, with a standard deviation of 260 kN. Its maximum value is 1464 kN, a quantity comparable with that registered in central Mexico [22]. In the next section the ground motion variable will be presented.

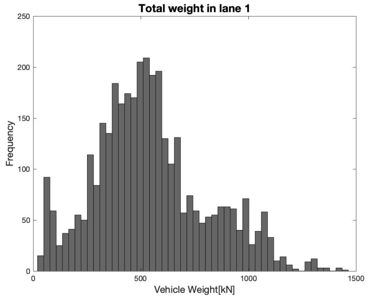


Figure 3: Total weight per lane (Source Dutch WIM data).

5.2. Ground motion

Unlike the previous variable, which was easy to operationalize, the ground motion can be represented in different manners. According to [24] the most widely used parameter in strong-motion studies is the peak ground acceleration (PGA). Essentially, it has been deemed superior compared to several intensity measures such as: peak ground velocity, peak ground displacement, spectral acceleration, Arias intensity, velocity intensity, cumulative absolute velocity and cumulative absolute displacement. Then, on the basis of efficiency, practicality, proficiency, sufficiency, and hazard computability, PGA is the optimal intensity measure [25] .

Having chosen the PGA measure, 12 three-components (longitudinal, transverse, and vertical) ground motions were used. They were proposed by Caltrans engineers from the Pacific Earthquake Engineering Research Center ground motion database [26]. Specifically, they were utilized in [27] in a probabilistic seismic demand analysis. To complement the previous database, the no-earthquake scenario and the ground motion occurred on 2017-09-19 in Mexico was also included, leading to a total of 14 records. These ground motions cover low, moderate, and high hazard seismic levels, as shown in Table 1.

Table 1: General characteristics of the ground motions.

Earthquake	Year	Station	PGA
No-earthquake	–	–	0.000
Morelos, MX	2017	DX37	0.191
Livermore, USA	1989	MGNP	0.245
Morgan Hill, USA	1984	CCLYD	0.273
Loma Prieta,USA	1989	LEX	0.403
Loma Prieta,USA	1989	GILB	0.447
Coyote Lake,USA	1979	CLYD	0.527
Parkfield,USA	1966	CS050	0.659
Loma Prieta, USA	1989	GAV	0.695
Loma Prieta, USA	1989	LGPC	0.783
Kobe, JP	1995	KOB	0.824
Tottori,JP	2000	TTR	0.975
Northridge, USA	1989	COR	1.026

The years of the events range from 1966 to 2017. While nine of them were recorded in the USA, two were registered in Japan and one in Mexico. Since all of them led to damage of RC bridge columns either by flexural or shear stresses [7], they were considered in the current research. Strictly speaking, only the Mexican record should be used in the assessment of the structure analyzed. Nevertheless, the use of the other ground motions helps to better understand the phenomena under study. Now that the first two categories of the framework have been established, the third will be presented.

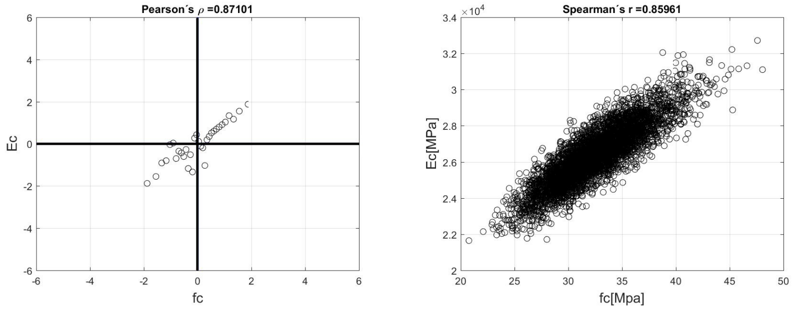
5.3. Bridge information

The Mexican bridge has already been described in terms of its geometry and reinforcement features (see Figure 1 above). To enhance the description, both its material properties and its finite element model will next be described.

5.3.1. Material properties

Four mechanical properties were introduced into the BN: concrete compressive strength ($f'c$), concrete elastic modulus (E_c), reinforced steel yield strength (fy) and tensile strength (f_u). These variables can be acquired in-situ according to the Mexican standards [28], [29], [30], [31], [32], [33] and [34]. The empirical part of the research consisted of collecting data from 64 fresh concrete cylindrical specimens, and 44 representative longitudinal reinforcement samples. They were obtained during the bridge construction process.

Due to the scarcity of field data, dependence models such as the gaussian copula can be employed to generate random data having the statistical characteristics of the specimens. Thereby, given the correlation between $f'c - Ec$ and $fy - fu$, a random gaussian copula is generated. First the Pearson's coefficient (ρ) is computed using a small sample of empirical data (see Figure 4a). Through equation (3) the associated Spearman's rank (r) is calculated (see Figure 4b). This enables to generate a larger sample of data based on the original data source.



(a) $f'c - Ec$ copula

(b) $f'c - Ec$ scatter plot

Figure 4: $f'c - Ec$ copula and scatter plot.

Once the random pair sample is computed, each material property is entered into the finite element model, which will now be described.

5.3.2. Finite element model

The numerical model is aimed at understanding the bridge behavior. The variables of interest here include: maximum axial load (MaxP), maximum shear (MaxV), maximum bending moment (MaxM), and lateral displacements (U). A simplified FEM of the structure has been built using SAP2000 v.14 bridge wizard module [35]. Following the guidelines for non-linear analysis of bridge structures [26], the subsequent assumptions are considered:

- Three component ground motion non-linear time history analysis is executed.
- Ground motions are amplified using a scale factor of 2.0.
- The interaction soil-structure is not taken into account and the ground is not modeled.
- Response in the inelastic interval is only evaluated for the RC column under study.
- Plastic hinges are placed at the ends of the column at 5% and 95% of the height.
- Springs are established at the beams support ends and over the cap.
- Negligible second-order effects ($P - \Delta$).
- Neoprene bearing pads only work as a simply supported system.
- Fixed joints are included in the column bottom.
- The Hilbert Hughes Taylor integration method is employed.

- The Mander parametric approach is utilized for concrete modeling.
- The simultaneous presence of two vehicles with random weight and positions on the bridge is contemplated.

Figure 5 shows the FEM simplified model. It should be observed that some springs have been included not only in the support ends but also in the bent cap. This is to consider damping effects during the simulation exercise. After the detailing of the three categories of the framework, the successive section the BN model will be proposed.

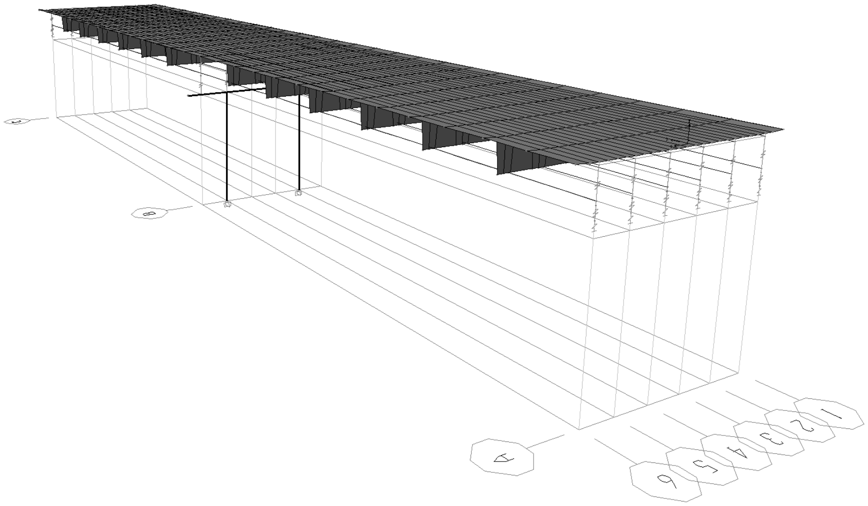


Figure 5: Simplified FEM model.

6. Bayesian network developed

The dependence structure of the data was modeled with a BN, that consists of 17 nodes (variables of interest) and more than 100 arcs illustrated in Figure 6. The model was built in the uncertainty analysis software package Uninet [36].

The occurrence of a seismic event of certain intensity (PGA) is independent of the vehicle weight in each lane of the bridge (WA1, WA2). The same is true for the number of axles in each lane (ApL1, ApL2) and the material properties $(f'c, Ec, fy, fu)$. WA1 and WA2 in turn, are independent from one another. Similarly, the material properties of the concrete $(f'c, Ec)$ are independent of the reinforcement steel strength (fy, fu). Moreover, ApL1 and ApL2 are conditionally independent of the force variables (MaxP, MaxV2, MaxV3, MaxM2, MaxM3) and the displacement variables (U1, U2, U3) given the loads on each section of the bridge.

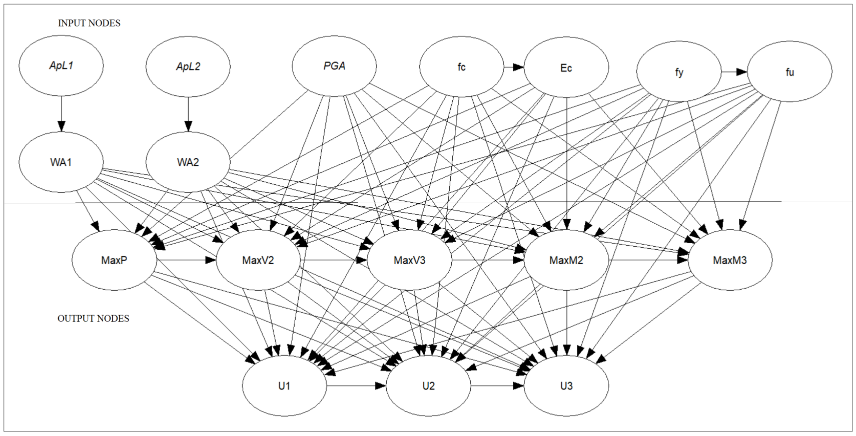
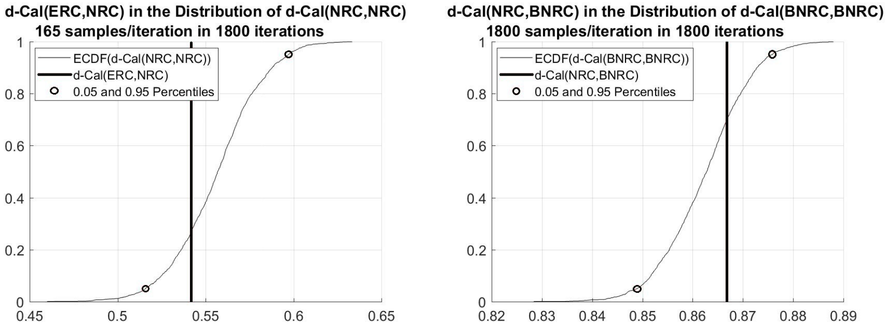


Figure 6: Proposed model.

The dependence between vehicles, earthquake intensity, material properties and force-displacement variables is complex. Hence, arcs from them to the remainder variables of the network are considered. The reason for this is that the BN model that would capture most of these interactions is precisely a complete graph (see the arrowheads converging in the output nodes in Figure 6). Once the graphical part of the model has been detailed, its validation process will be described.

6.1. Validation of the model

The dependence calibration score was estimated to validate the BN using Equation (4). Based on the approach exposed in [18] for calculating the d-score, a sample of 165 observations was generated 1800 times. This resulted in a d-score of 0.54, showing that the data has a normal copula (see Figure 7a ERC vs NRC). Similary, the resultant d-score between BNRC and NRC equals 0.868, demonstrating that the BN dependence is enough (see Figure 7b). This analysis concluded that the model was valid, hence valid reliability assessments can be carried out.



(a) The d-score of the ERC vs NRC

(b) The d-score of the BNRC vs NRC

Figure 7: Dependence calibration score.

7. Reliability analysis

The Oxford English Dictionary [37] defines reliability as *"the quality of being trustworthy or of performing consistently well"*. This definition is higly associated with the assessment of the POF [38]. To evaluate such a probability, a limit state function (Z) should be prior defined. In this case, Z is the condition beyond which, the structure or part of the structure does not longer fulfill one of its performance requirements. The limit state Z can be assessed by considering the resistance R and the loads L, i.e. $Z = L - R$. Failure occurs when $L > R$. Then, the probability of failure equals:

$$P_f = P(Z \geq 0) \tag{6}$$

As mentioned earlier, for the RC column analyzed, R will be estimated using the approach described in section 3. ln contrast, L will be obtained from the FEM analysis. Subsequently, the limit state functions required will be established.

7.1. Combined axial and flexural strength limit state function

The limit state function Z_{BC} is assessed by considering the position of the point (MaxM, MaxP) in the corresponding interaction diagram. The following two conditions are considered:

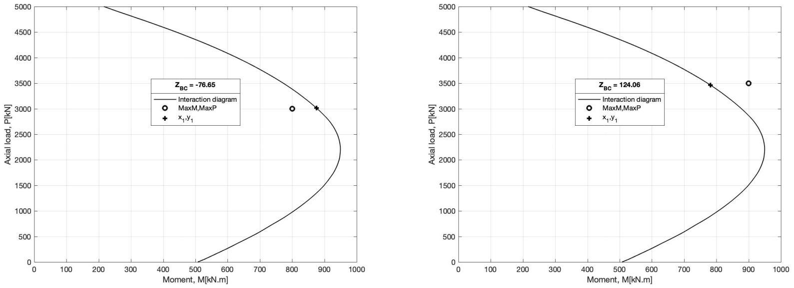
if the point is inside of the diagram area:

$$Z_{BC} = -1 * \sqrt{(MaxM - x_1)^2 + (MaxP - y_1)^2} \tag{7}$$

if the point is outside of the diagram area:

$$Z_{BC} = \sqrt{(MaxM - x_1)^2 + (MaxP - y_1)^2} \tag{8}$$

Where (x_1, y_1) are the coordinates of the closest point on the interaction diagram boundary to the point (MaxM, MaxP). Failure occurs when $Z_{BC} > 0$. Figure 8 shows two examples of the Z_{BC} value.



(a) (MaxM, MaxP) combination inside the interaction diagram, negative Z_{BC} value

(b) (MaxM, MaxP) combination outside the interaction diagram, positive Z_{BC} value

Figure 8: Z_{BC} value.

Therefore, the POF due to combined axial and flexural strength equals:

$$P_{fBC} = P(Z_{BC} \geq 0) \tag{9}$$

7.2. Shear strength limit state function

Here, the shear strength function Z_{Sh} is assessed by means of Vu, and the maximum acting shear in the element $(MaxV)$.

$$Z_{Sh} = MaxV - Vu \tag{10}$$

Thus, the POF due to shear (P_{fSh}) is:

$$P_{fSh} = P(Z_Sh \geq 0) \tag{11}$$

7.3. Drift exceedance limit state function

Finally the drift exceedance function Z_γ is computed through γ and the maximum permissible drift γ_{max}.

$$Z_\gamma = \gamma - \gamma_{max} \tag{12}$$

The drift exceedance probability $(P_{f\gamma})$ is:

$$P_{f\gamma} = P(Z_\gamma \geq 0) \tag{13}$$

Once the model has been fully explained, its application will be presented in the next section, together with an analysis and discussion of its results.

8. Analysis and discussion

One of the advantages of the BN model, is that whenever evidence becomes available, the joint distribution may be updated accordingly. This procedure is referred to as conditionalization. Then, the BN is ready to be used for inference processes. It is also possible to condition either a unique value, or an interval.

In order to understand the use of the BN model, the instantiation process of the input nodes, using the PGA variable, will be illustrated. Making use of the intensities already presented in the last column of Table 1, they are firstly ranked from the minimum to the maximum value i.e. 0.00 to 1.026. Secondly, the 25th and 75th percentile values are calculated. In this case, they correspond to 0.273 and 0.783 respectively. Then, three ranges are proposed: (0.00,0.273) for low ground motion intensities; (0.273,0.783) for mid ground motion intensities; and (0.783,1.026) for high ground motion intensities.

The same steps are followed with the remainder selected input variables (WA1, WA2, $f'c, fy$). With this approach, 243 (3^5) scenarios can be analyzed. Each may help to determine the POF of the RC column subject to the combined action of, say, axial and flexural strength. Table 2 shows both the quantitative ranges found, and their qualitative labels.

Table 2: Input node labels.

Input node	LB	UB	Label
PGA[g]	0.000	0.273	Low
	0.273	0.783	Middle
	0.783	1.026	High
WA1[kN]	21.80	372.0	Low
	372.0	676.0	Middle
	676.0	1464.4	High
WA2[kN]	43.70	378.8	Low
	378.8	705.0	Middle
	705.0	1464.4	High
$f'c$[MPa]	22.70	30.00	Low
	30.00	34.80	Middle
	34.80	47.90	High
fy[MPa]	345.5	435.0	Low
	435.0	484.0	Middle
	484.0	619.7	High

To demonstrate the use of the BN in practice, an example is now provided. Suppose that the following scenario is randomly generated: PGA_{Middle}, $WA1_{High}$, $WA2_{High}$, fc_{Low}, and fy_{Low}. Essentially, it represents a situation with considerable vehicle loads and low material resistances. Using a sample that satisfies the conditionalization of the five input variables, the limit state function (Z_{BC}) is evaluated. By means of an exceedance probability analysis [18], a POF=$3.35x10^{-7}$ is calculated. This probability is in line with the figures reported in [39], and corresponds to a small failure rate (lower than $1x10^{-6}$).

Figure 9 shows graphically the cumulative exceedance probability for this condition. While the black line represents the empirical distribution of Z_{BC}, the dotted one represents the corresponding extrapolation. As can be seen, the sample obtained from the conditionalized BN was not enough to reach the failure state $Z_{BC} \geq 0$. In consequence, a t location-scale fitted function with parameters $\mu = -216.51$, $\sigma = 27.773$, and $\nu = 16.35$ was required to find out the POF.

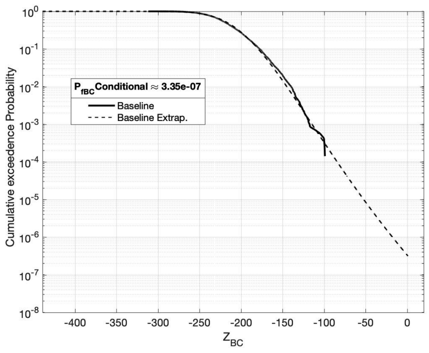


Figure 9: Conditional POF for the following case: PGA_{Middle}, $WA1_{High}$, $WA2_{High}$, fc_{Low}, and fy_{Low}.

Given the large number of possible cases, 15 scenarios have been chosen for further analysis. The criteria for selection were as follows: one third of the events correspond to a low PGA, one third to a middle PGA and one third to a high PGA. For the loads ($WA1$ and $WA2$) and the resistances (fc and fy) there were 81 combinations, but only five were used because it was felt that they would give a general insight of the seeked probabilities. They are: (High-High, Low-Low), (Low-Low,Low-Low), (High-High, High-High), (Low-Low, High-High) and (Middle-Middle, Middle-Middle) respectively. Table 3 summarizes not only the described scenarios but also their associated probabilities of failure. Note that three POF's are being reported: P_{fBC}, P_{fSh} and $P_{f\gamma}$.

Table 3: Probability of failures for each case

Cases	Peak Ground Acceleration (PGA)	Total weight per lane (WA)	Materials Resistance (f'c, fy)	P_{fBC}	P_{fSh}	$P_{f\gamma}$
	Level of conditionalization					
1	Low	High, High	Low, Low	2.24E-07	6.53E-04	3.62E-05
2		Low, Low	Low, Low	1.58E-07	9.46E-04	1.50E-05
3		High, High	High, High	1.11E-16	4.67E-11	2.99E-06
4		Low, Low	High, High	4.88E-15	1.33E-11	4.96E-06
5		Middle, Middle	Middle,Middle	3.33E-16	1.17E-08	6.10E-07
6	Middle	High, High	Low, Low	3.35E-07	1.28E-03	3.19E-04
7		Low, Low	Low, Low	2.17E-07	1.43E-04	1.64E-04
8		High, High	High, High	1.44E-14	7.49E-11	2.67E-05
9		Low, Low	High, High	3.57E-14	6.73E-11	2.63E-05
10		Middle, Middle	Middle, Middle	2.22E-16	7.61E-08	4.70E-05
11	High	High, High	Low, Low	1.09E-07	9.65E-04	4.17E-03
12		Low, Low	Low, Low	2.47E-07	5.39E-04	3.15E-03
13		High,High	High,High	1.11E-16	1.04E-11	4.32E-04
14		Low, Low	High,High	2.22E-16	6.37E-12	1.78E-04
15		Middle, Middle	Middle, Middle	1.45E-10	1.27E-07	1.32E-03

For the combined axial and flexural strength, three of the most adverse scenarios are given by PGA_{Low}, $WA1_{Low}$, $WA2_{Low}$, fc_{Low}, and fy_{Low} (case 2) with a $P_{fBC} \approx 1.58x10^{-7}$, case 7 with a $P_{fBC} \approx 2.17x10^{-7}$ and case 12 with a $P_{fBC} \approx 2.47x10^{-7}$. Once more, all of them are lower than $1x10^{-6}$, ratifying small failure rates [39]. It becomes apparent that the PGA has minimum influence in the P_{fBC}. However, it reveals the importance of the quality controls during the construction process, to avoid low material resistances.

In terms of the shear strength, case 6 represents the worst possible event with a $P_{fSh} \approx 1.28x10^{-3}$. This value corresponds to a large failure rate (close to $1x10^{-3}$) [39]. Now, for a middle PGA, the vehicle loads have an important influence in P_{fSh}, given low material resistances. It is worth noting that the P_{fSh} for case 7 is lower one order of magnitude than that for case 6. Moreover, it is lower eight orders of magnitude with respect to case 8 ($P_{fSh} \approx 7.49x10^{-11}$). This confirms the importance of quality controls to ensure high material resistances during the building stage.

Last but not least is the drift exceedance. Case 11 with a $P_{f\gamma} \approx 4.17x10^{-3}$ is now the most adverse scenario. This value is 1.3 times that of case 12 ($P_{f\gamma} \approx 3.15x10^{-3}$), meaning that the lower the vehicle loads, the lower the probability of failure. At this point, it was expected to obtain similar trends as those stated in [1]. Contrary to the finding reported here, they found a beneficial effect due to the presence of live loads. This was evidenced by the reduction of the measured displacements and probability of failure. In the same line of thought, more analysis may be performed. Those presented here have demonstrated the value of the proposed BN model. Finally, the main conclusions of this research will subsequently be drawn.

9. Conclusions

This document has dealt with concrete RC bridge columns and their acting loads and materials resistances. Having reviewed the literature, it became apparent that the combination of earthquake and live loads could lead to the failure of the structure under analysis. To better comprehend the bridge behavior, a probabilistic model was develop using the BN framework.

The proposed network includes the following variables: number of axles per lane, peak ground acceleration, total vehicle weight per lane, steel yield strength, tensile strength of the steel, compressive concrete strength, modulus of elasticity of the concrete, maximum axial load, maximum shear, maximum bending moment and displacements.

After quantifying all 17 variables by means of statistical historical data, in-situ tests and Monte Carlo simulations, their probability distributions were established. All of them were represented through empirical distributions, allowing the analyst to calculate the RC POF's. The most adverse calculated POF due to combined axial and flexural strength is approximately $3.35x10^{-7}$. The worst calculated POF due to shear force is approximately $1.28x10^{-3}$ and the most adverse for the maximum drift exceedance is approximately $4.17x10^{-3}$. Moreover, some scenarios can be simulated with the model. The results have the potential to help bridge managers in the resources allocation based on new available data.

Therefore, it is strongly believed that the methodology applied to build the model herein presented should serve as a benchmark. Basically, it might be applied to complete related exercises in different locations.

While the key objectives of this research have been achieved, there were a number of drawbacks associated with the work. Firstly, the limited availability of data records for quantifying the variables. Secondly, the use of in-situ tests has proven to be a time-consuming aspect for collecting information.

Overall, this research has demonstrated that the use of continuous probability distributions, generated through statistical data in concrete bridge columns, is not only reasonable but also advantageous. Even more, with new information the results can be updated through the proposed BN.

This work forms part of a bigger project aimed at developing a more comprehensive model applicable to the different components of a bridge. Finally, it is hoped that the results presented in this document are useful for the civil engineering community.

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ANEXO

Manuscript Details

Manuscript number	ENGSTRUCT_2018_3372
Title	Reliability analysis of reinforced concrete vehicle bridges columns using nonparametric Bayesian networks
Article type	Research Paper

Abstract

In the bridge industry, current traffic trends have increased the likelihood of having the simultaneous presence of both extreme live loads and earthquake events. To date, their concurrent interaction has scarcely been systematically studied. Prevailing studies have investigated the isolated existence of either live loads or seismic actions. \\ In an effort to fill this gap in the literature, a non-parametric Bayesian Network (BN) has been proposed. It is aimed at evaluating the conditional probability of failure for a reinforced concrete bridge column, subject simultaneously to the actions mentioned above. Based on actual data from a structure located in the State of Mexico, a Monte Carlo Simulation model was developed. This led to the construction of a BN with 17 variables.\\ The set of variables included in the model can be categorized into three groups: acting loads, materials resistances and structure force-displacement behavior. Practitioners are then provided with a tool for unspecialized labor force to gather information in-situ (e.g. Weight-In-Motion data and Schmidt hammer measurements), which can be included in the network, leading to an updated probability of failure. Moreover, this framework also serves as a quantitative tool for bridge column reliability assessments.\\ Results from the theoretical model confirmed that the bridge column probability of failure was within the expected range reported in the literature. This reflects not only the appropriateness of its design but also the suitability of the proposed BN for reliability analysis.\\

Keywords	Bridge; reliability; Reinforced concrete column; bayesian networks
Taxonomy	Reliability Estimation, Seismic Hazard, Structural Safety, Limit State Design, Column Base
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29/Oct/2018

Dear Dr. Phillip L. Gould
Editor-in-Chief Engineering Structures

We wish to submit the manuscript entitled “Reliability analysis of reinforced concrete vehicle bridges columns using nonparametric Bayesian networks”, for consideration by the Journal of Engineering Structures.

In this document, we report on the results of a non-parametric Bayesian network (NPBN) aimed at evaluating the behavior of a reinforced concrete column under live loads and seismic scenario. The results are comparable to those already reported in the literature. Then, the paper should be of interest to readers in the areas of reliability management of bridges structures.

In general, it is believed that this is one of the first studies carried out in Mexico that make use of NPBN, to assess the phenomena of interest. Overall, bridge management agencies require more information about the state of the art tools designed for reliability and safety analysis.

We confirm that this work is original and has not been published elsewhere nor is it currently under consideration for publication in another place. Please address all correspondence concerning this manuscript to me at mendozalugo@gmail.com.

Thank you for your consideration of this manuscript.

Sincerely,

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Reliability analysis of reinforced concrete vehicle bridges columns using nonparametric Bayesian networks

Highlights

- This research deals with reinforced concrete columns behavior and under live loads and seismic event.
- The use of NPBN and MCS could lead to the development of a management decision tool.
- The results may be used for ranking investments in maintenance actions.
- This model is in agreement with the estimates given in reliability literature.