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Reliability Assessment Methodology of Blast Protective Steel Moment Resisting Frame Using NiTi SMA-based Connection

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Abstract

This paper proposes a methodology framework for the reliability assessment of smart steel Moment Resisting Frame structures (MRFs) equipped with Nickle Titanium Shape Memory Alloy (NiTi SMA) connections subjected to blast loading. The reliability assessment framework is formulated based on a two-step approach algorithm. In the 1st Step, the Monte Carlo Latin Hypercube Sampling Strategy simulation (MC-LHS) is adapted to generate the uncertain parameters sample points. Considering the numerical simulations, the 2nd Step employs simplified performance functions and the generated random outcomes from the 1st Step. The proposed reliability approach is verified against direct Monte Carlo Simulation (MCS) and First-Order Reliability Method (FORM). The performance functions are columns' axial force and bending moments, rotation capacity at the connections, and Inter-Story Drift Ratio (ISDR). Throughout the development of the reliability assessment, the probabilistic models are parametrized on geometrical properties, material properties, vertical loads, model errors, and charge weights. The developed reliability framework is applied to a prototype 4-story smart MRF. The structural safety level is obtained in terms of the Reliability Index (β). The results show that the reliability framework provides an accurate and efficient structural collapse prediction of the MRFs equipped with NiTi SMA-based connections. Finally, sensitivity analysis is performed to indicate the sensitivity of building collapse to blast wave characteristics, material strength, vertical gravity loads, and column profile dimensions. The sensitivity analysis results also confirm the efficiency of the proposed reliability framework in observing the highly sensitive parameters, which is explosive charge weight.

Keywords

smart structure, reliability assessment, explosion, sensitivity analysis

1 Introduction

Explosions, terrorist attacks, and accidental explosions are a growing concern of private and governmental agencies. Conventional steel structures are more prone to collapse due to the extreme effect of explosions, and they are designed for ultimate or serviceability limit state for individual or combination of dead load, live load, earthquake, and wind loads. Numerous research projects investigated the behavior of beam-to-column steel connections subjected to intentional explosions. Various techniques were used to improve the beam-to-column connection panel, e.g., fin plate [1], post-Northridge steel connection (moment connection) [2], strengthening connection region [3], and shear tab connection [4]. After the Northridge earthquake, the Moment Resisting Frame (MRF) connections showed improvement in structural lateral resisting subjected to the seismic application [5]. Despite the improved seismic performance, yet plastic deformation can be noticed after major earthquakes [6]. Few research projects proposed further improvement of the panel zone of steel column to beam connection and prevent residual stress concentration. Nickle Titanium Shape Memory Alloy (NiTi SMA) is one of the efforts, and it was widely embedded in the connection as bolts [7] and tendons [8] to alter the damage mode and avoid inelastic residual deformation in the seismic application. Recently, a series of publications from the authors [9–11] provided ground shreds of evidence of the application of NiTi SMA-based connections under blast loadings. The studies assessed the behavior of steel MRFs equipped with NiTi SMA bolts deterministically. The studies showed that the smart connection improves the MRFs' energy capacity and prevents inelastic deformation in the columns and/or beams. Accordingly, a set of key design procedure rules are proposed for daily life practice engineering to facilitate the design processes.

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Few studies have been conducted on the system-level evaluation of the steel structures considering the high uncertainties attached to the blast loading parameters [12] and material strength [13]. Therefore, the reliability design-based approach is considered an accepted methodology for quantifying the risks associated with structural collapse. Kumar and Matsagar [14] and Khan et al. [15] studied the fragility of steel Moment Resisting Frames (MRF) with irregularities. They considered explosive material charge weight and the standoff distance as random variables. Ding et al. [16] investigated the failure probability of steel structures subjected to explosions. They proposed a two-step approach. Both the subset simulation approach and the Delayed Rejection Adaptive Markov Chain Monte Carlo simulation algorithm are used. Blast load, vertical gravity loadings, and material properties are considered as uncertain parameters. They confirmed that the result of the study is accurate and efficient. With different simulation techniques, Bayesian logistic regression method, Song [17] developed the fragility function, which is parametrized on blast wave and material characteristics. Other studies used different probabilistic approaches for the concrete structural elements, e.g., concrete beams [18], concrete columns [19], walls [20], and dome structures [21]. However, very few studies covered the probabilistic investigation of connections of steel structures in the system-level environment.

For the local-level structural member evaluation, a few research works included probabilistic analysis in their studies. Liu and Dawood [22] presented a reliability analysis of the influence of debonding in steel beams. They strengthened the steel beam with externally bonded carbon fiber-reinforced polymer (CFRP) composites. Another probabilistic framework of steel columns is proposed by Singh et al. [23] to estimate the failure probability. Two limit states are considered, namely limit state function of flexure and global buckling, to parametrize the column's blast loading profile. Markova et al. [24] performed a reliability analysis on basic structural members to achieve the required safety level by Eurocode [25]. The report indicated that the structural members' reliability levels for most imposed action categories exceed the reliability indices recommended in [25]. Further study was conducted by Hadianfard et al. [26] to obtain a failure probability of H-section steel columns subjected to various blast scenarios. The axial load-bearing capacity damage index is used to observe the structural damage. Detta et al. [27] proposed an efficient, robust optimization approach for structures subjected to various underground explosions.

One can say that one of the drawbacks of the proposed approaches in the literature is that they are designed for specific-related purposes. Another drawback is that the developed approaches rarely can achieve an extremely low probability of failure, e.g., 1×10^{-5} and even smaller. The further weak point is that very few attempts involved stochastic analysis concerning steel structures (global level), structural steel members (local level), and steel structures equipped with smart connections subjected to blast loading. Inspired by the above shortcomings, the current study attempted to develop a reliable framework to evaluate MRFs equipped with smart connections developed by the authors [9] probabilistically.

Herein, this study developed a state of art reliability framework approach to carry out the reliability analysis of smart steel MRF equipped with NiTi SMA connections. The reliability framework consists of a two-step approach. In the 1st Step, using Monte Carlo-Latin Hypercube Sampling strategy (MC-LHS) simulation and considering various uncertain parameters, 350 sample points are generated. The column section geometrical properties, material characteristics, imposed live loads, dead loads, and blast wave parameters are considered uncertain random variables. The 2nd Step starts with the numerical simulation of the smart MRFs. The numerical analysis outcomes are collected and stored in the designated database for reliability analysis. Three performance functions are formulated, which are parametrized on axial force and bending moments (global buckling) in the columns, maximum rotation capacity at the connections, and Inter-Story Drift Ratio (ISDR). The proposed reliability algorithm is validated against MCS and FORM analysis. The proposed approach is then applied to obtain the safety level of smart MRFs. Finally, sensitivity analysis is performed to observe the most sensitive uncertain parameters. The results of this paper can be used as a basis for the probabilistic assessment of MRFs subjected to blast loading.

2 Computation of blast loading parameters

The proposed smart structure is subjected to Vehicle Borne Improvised Explosive Device (VBIED). Matlab (R2021a) software is used to prepare the code of the blast loading calculation auto framework [28]. Simplified Kingery Airblast polynomial curve fitting equations are used to compute the blast loading profile [29]. The blast loading profile consists of arrival time, positive phase duration, rise time, negative phase duration, angle of incident, incident and reflected over-pressure, and incident and reflected impulse. The details and validation are given in [9].

3 Framework of reliability analysis

3.1 Latin hypercube sampling strategy

Because of the ease of implementation and its ability to handle huge and complicated engineering problems, reliability-based Monte Carlo Simulation (MCS) is widely used to resolve engineering problems. However, a huge computational time is required to acquire sufficient accuracy in the case of blast analysis in which the failure probability is very small. To reduce the computational time, Latin Hypercube Sampling (LHS) is used [30]. LHS avoids repetition in the sampling scheme; thus, the number of samples is reduced drastically. In addition, LHS samples from the tails of the distribution accurately. This is very important for blast events, which possess a very low probability of occurrence-high consequences.

3.2 Proposed reliability assessment algorithm

The proposed reliability assessment framework is presented in Fig. 1. The framework is dealt with as a two-step approach. To master the understanding of the proposed reliability approach, the following steps are explained in detail:

1st Step

Fig. 2 presents the step-by-step procedures to apply the 1st Step of the proposed reliability framework approach.

1. In the 1st Step, using MC-LHS, 350 sample points are generated. The proposed algorithms are validated against direct Monte Carlo Simulation (MCS) and First Order Reliability Method (FORM). Further details are given in Section 3.4.

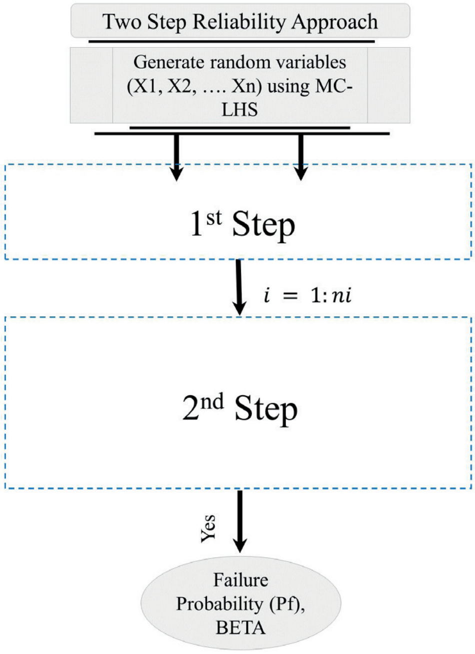

Fig. 1 Reliability assessment framework

2. The uncertain parameters set is divided into three category parameters for columns, axial force resistance (N_{Rk}), bending moment resistance (M_{yRk}), explosive material charge weight (human error factor related to the variation of the desired mass of explosion (W_{user}), a factor related to the variation of volume and/or mass of the explosion due to manufacturing error (W_{NEQ}), column dimensions, material strength (F_y), and vertical gravity loads.

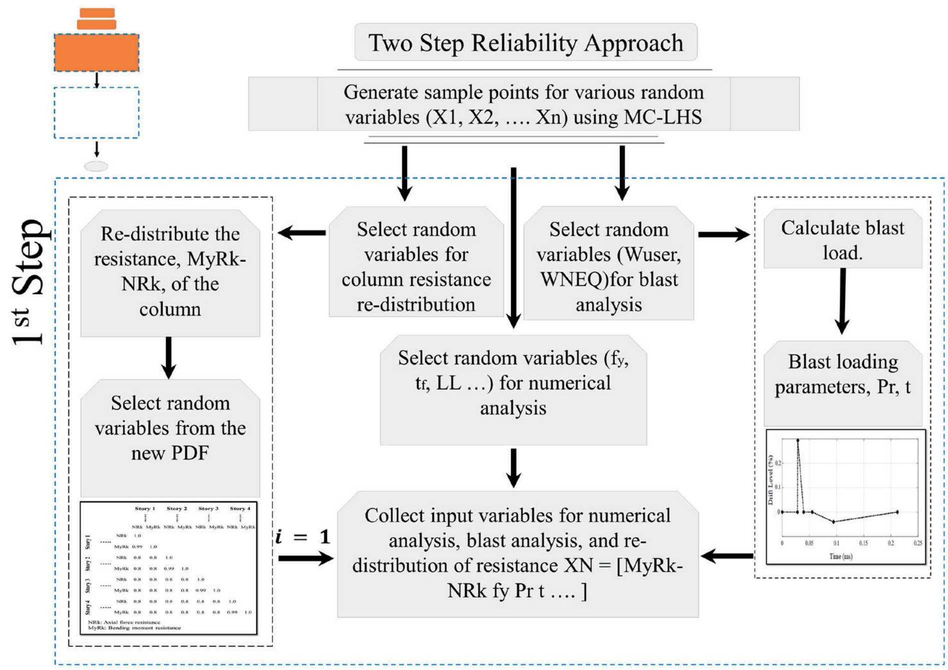

Fig. 2 Reliability assessment framework-1st step

3. To account for, first, the moment-axial force interaction correlation in the columns, second, the interaction correlation of moment-axial forces between the columns at the same story level. And third, the interaction correlation of moment-axial forces between columns at subsequent story levels, the columns' resistance parameters (N_{yRk}, M_{yRk}) are redistributed by using the correlation matrix. Following this, a new Probability Distribution Function (PDF) is generated. Later, the sample points from the new PDF are collected for numerical analysis. The results revealed that the reliability and sensitivity analysis results are independent of the correlation matrix.
4. The blast loading simulation is started by using the associated random variables, W_{user} and W_{NEQ}. The blast loading profile parameters are generated and collected to proceed with the numerical analysis of the smart MRFs.
5. The rest of the random variable sample points are directly used as input parameters in the numerical analysis of the smart MRFs.

2nd Step

Fig. 3 presents the step-by-step procedures to apply the 2nd Step of the proposed reliability framework approach.

1. Using the random variable for each sample point produced in the 1st Step, the numerical analysis is conducted by OpenSees [31].
2. Following the numerical analysis, the response of the numerical simulation is collected in the designated database. The random response outcomes (design value of the maximum moment M_{yEd}, the design value of axial force N_{yEd}), End column rotation (NiTi SMA-based connection rotation), and Inter Story Drift Ratio (ISDR)) from the numerical analysis are considered as demand sample distributions. Similarly, the capacity sample distributions have been generated from the column resistance parameters (N_{yRk}, M_{yRk}), probabilistic connection rotation thresholds, and probabilistic ISDR thresholds. The connection rotation threshold is obtained from the moment rotation capacity curve of the fully detailed NiTi SMA-based connection, while the drift

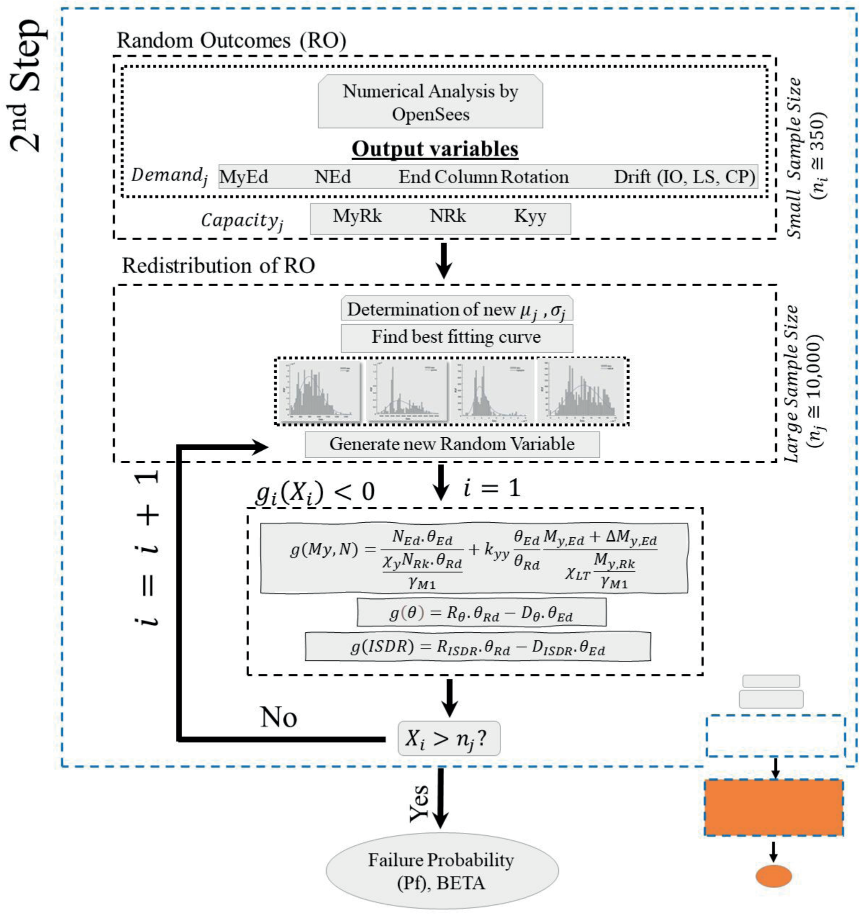

Fig. 3 Reliability assessment framework-2nd step capacity thresholds are taken from FEMA-356 [5]. With the help of model error distribution, the thresholds are used in the form of a capacity distribution instead of one single value threshold.

3. To satisfy the requirements of the Joint Committee on Structural Safety (JCSS) [32] and ISO 2394 [33], a very high target Reliability Index (β) is needed. In another meaning, at least 10,000 sample points are needed to achieve such a very high β.
4. Therefore, based on the 350 outcome sample points from the numerical analysis, the statistical parameters of the demand distribution function, capacity distribution functions, and the type of distributions are obtained using the curve fitting analysis approach. Later, MC-LHS is used to generate 10,000 demand and capacity sample points.
5. Considering the model error embedded in the performance functions, the target reliability indices (β) are determined. Details of performance functions of various intensity levels and validation models are given in the following sections.

3.3 Performance functions

In this study, three limit state functions are used. First, the columns' general form of global buckling resistance is given in Eurocode 3 [34]. The vertical members are subjected to combined axial compression and bending in blast events. The first check shall satisfy the following conditions:

$$g_1\left(My,N\right)=\frac{N_{Ed}\theta_{Ed}}{\frac{\chi_y N_{Rk}}{\gamma_{M1}}\theta_{Rk}}+k_{yy}\frac{\theta_{Ed}}{\theta_{Rk}}\frac{M_{y,Ed}+\Delta M_{y,Ed}}{\chi_{LT}\frac{M_{y,Rk}}{\gamma_{M1}}}+k_{yz}\frac{\theta_{Ed}}{\theta_{Rk}}\frac{M_{z,Ed}+\Delta M_{z,Ed}}{\frac{M_{z,Rk}}{\gamma_{M1}}}, \tag{1}$$

where $g_1(My,N)$ is the limit state function of combined bending moment and axial compression. N_{Ed}, $M_{y,Ed}$, and $M_{z,Ed}$ are the design values of the compression force and the maximum moments of the y-y and z-z axis along the member, respectively. Since the problem is 2D, the design values in the z-z axis are neglected. $\Delta M_{y,Ed}$, and $\Delta M_{z,Ed}$ are the moments due to the shift of the centroidal axis. The cross-sectional class of the column members is either class 2 or class 3; therefore, the centroidal axis effect is neglected. χ_y, and χ_{LT} are the reduction factor due to flexural buckling and lateral torsional buckling, respectively. k_{yy}, and k_{yz} are interaction factors. θ_{Ed} and θ_{Rk} are the demand and resistance model errors.

The failure of the column under combined loading is conditional on the value of Eq. (1). The performance function is defined such that:

$$P_f\left(My,N\right)=\begin{cases}<1 & \text{the structure is safe}\\ =1 & \text{on the limit state}\\ >1 & \text{the structure failed}\end{cases}. \tag{2}$$

Second, the maximum rotation demand (D_θ) of the embedded smart connection in 2D MRFs. The rotational capacity, Immediate Occupancy of rotation ($R_{\theta-IO}$), Life Safety ($R_{\theta-LS}$) and Collapse Prevention ($R_{\theta-CP}$), are taken from the local model moment rotation capacity curve developed by Weli and Vigh [35]. Fig. 4 shows the performance level of the conventional steel structure FEMA 356 [5] and the smart structure. With reference to [5], the following hazard level representation is introduced for smart steel structures. $R_{\theta-IO}$ corresponds to the first stress transformation (σ_{MS}), for which the main structural element remains intact, any repairs are minor. At the Life Safety hazard level of rotation ($R_{\theta-LS}$), the structure may experience damage, however the risk to life safety is low. When the structure reaches $R_{\theta-CP}$, the building poses a significant risk to life safety, and it is a complete economic loss. Accordingly, the threshold of $R_{\theta-IO}$, $R_{\theta-LS}$ and $R_{\theta-CP}$ are 0.005 rad, 0.008 rad, and 0.016 rad, respectively. The limit state function of connection rotation ($g_2(\theta)$) is shown in Eq. (3) and Eq. (4):

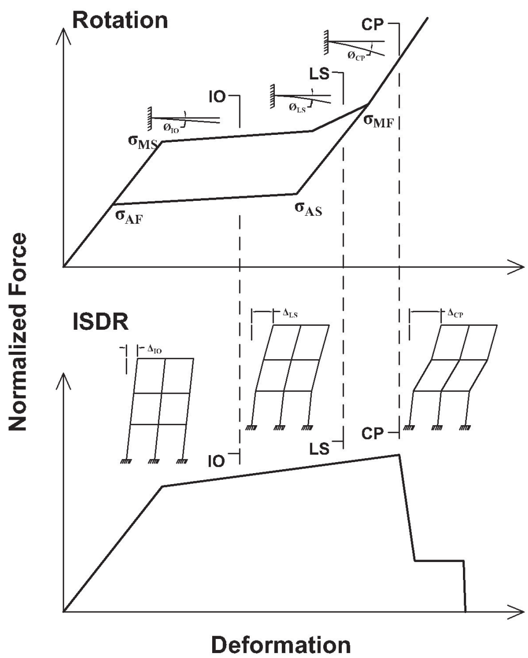

Fig. 4 Performance level of target building, FEMA 356 (bottom) and current study (top)

$$g_2(\theta) = R_\theta \theta_{Rd} - D_\theta \theta_{Ed}, \quad (3)$$

$$P_f(\theta) = \frac{1}{N} \sum_{i=1}^{N} g\left(\theta_i \langle 0 | I_\theta, \varnothing_{i_1,..,i_n}\right), \quad (4)$$

where $P_f(\theta)$ is the probability of failure conditional on $R_{\theta-IO}$, $R_{\theta-LS}$ and $R_{\theta-CP}$ hazard levels, N is the sample size, $g(\theta)$ is the limit state function of rotation, and θ_i is the rotation in the connection due to various random variables ($\varnothing_{i_1,\ldots,i_n}$).

Third, Inter Story Drift Ratio (ISDR), three intensity levels of ISDR are introduced as the threshold of a limit state function, Immediate Occupancy (IO), Life Safety (LS), and Collapse Prevention (CP), which are given in FEMA 356 [5]. The given values are for seismic applications and conventional structures. Therefore, the thresholds are modified for the proposed structural and loading case type. The ISDR value of CP, 0.05%, is taken as a reference value. Equivalent to the corresponding rotational capacity thresholds, $R_{\theta-IO}$ and $R_{\theta-LS}$, the IO and LS of ISDR are obtained as 0.015% and 0.025%, respectively. This modification allows for including the influence of hysteresis behavior of smart connection and aligns with the requirement of reliable structure in Eurocode [25].

$$g_3(ISDR) = R_{ISDR} ISDR_{Rd} - D_{ISDR} ISDR_{Ed}, \quad (5)$$

$$P_f(ISDR) = \frac{1}{N} \sum_{i=1}^{N} g\left(ISDR_i \langle 0 | I_k, \vartheta_{i_1,..,i_n}\right), \quad (6)$$

where $g_3(ISDR)$ is the limit state function of ISDR, R_{ISDR} is ISDR capacity thresholds, D_{ISDR} is the ISDR demand of the smart MRF, $P_f(D_{ISDR})$ is the probability of failure conditional on a certain hazard level (I_k) and various random variables ($\vartheta_{i_1,\ldots,i_n}$). It is worth to mention that the uncertain parameters distribution type in the 1st Step are presented in the first table in Section 5.2. However, the distribution of the uncertain demand and capacity statistical parameters in the 2nd Step is obtained based on the results of curve fitting analysis.

3.4 Validation model

The proposed algorithm is validated with direct MCS and First Order Reliability Method (FORM). The single bay 2D frame model is developed in OpenSees [31]. The blast load profile is generated and applied to the front face of the 2D single frame (as shown in Fig. 5). The charge weight, dead weight (W), modulus of elasticity (E), and material strength (F_y) are considered as random variables. Combined bending and axial compression in the columns and ISDR are the performance functions to obtain failure probability. Applying FORM analysis requires the ingredients of the limit state function equation. For such a simple example, Slope Deflection Method (SDM) is used to derive the equation of design loads and induced ISDR.

For the MCS and LHS, 10,000 and 350 samples were run by OpenSees software, respectively. Fig. 6 shows the results of the validation model analysis. Compared to MCS, considerable accuracy can be achieved with a significantly smaller sample size. The reliability of the limit state functions is verified with the equations and ingredients of FORM analysis. The effect of the sample size is shown in Fig. 7. It is evident that 350 sample points are sufficient to obtain an accurate Reliability Index (β).

4 Numerical simulations

4.1 Smart connection description

Following the Eurocode complying key design procedures developed by the authors in the previous studies, the fully detailed smart connection equipped with NiTi SMA is developed using a Mechanical APDL solver in

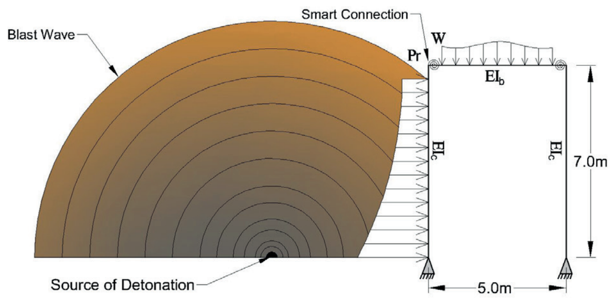

Fig. 5 2D single frame validation model

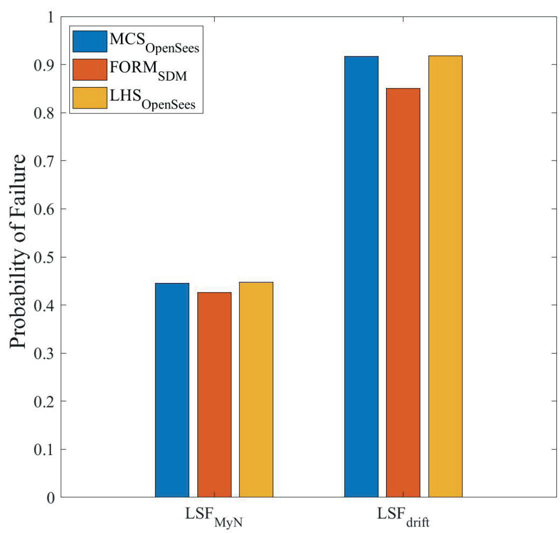

Fig. 6 Probability of failure of MCS vs LHS vs FORM analysis

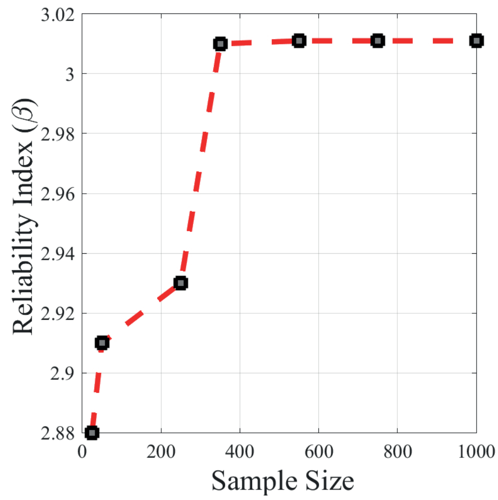

Fig. 7 Sample size convergence

the FE software ANSYS [36]. The NiTi SMA-based connection consists of a steel IPE beam, HEA columns, end-plate, stiffeners, and NiTi SMA bolts as shown in Fig. 8. The fully detailed NiTi SMA-based connection is subjected to a blast load-like profile. Since the required computational time to run the fully detailed NiTi-SMA-based connection model is cumbersome, the model is intended to be simplified (see Fig. 8 red color). OpenSees platform is used to model the simplified connection with rotational springs. This Step is essential when the local connection is employed in the 2D MRF analysis. More details about the FEM methods, experimental validation of the blast modeling simulation, and structural modeling are given in [9–11] and [29].

Accordingly, the key design features are:

- The effect of strain rate is counted.
- The smart connection is classified as Partially-Strength and semi-rigid.
- Bolt failure, martensite phase activation, is prioritized as the governing failure mode in the early design stage, conforming to Eurocode 3 [37].
- Residual stress concentration in the steel components is avoided.
- Moderate and Low Ductility Classes are preferred in the MRF analysis of Moment Resisting Frame structures (MRFs).

4.2 Prototype smart building

The above design procedures are used to develop 4 story 2D MRF prototype building. The building prototype is a residential building and has 3 bays in each direction. 6 m length in the longitudinal direction and 4 m width in the transverse direction. The analysis is performed on the typical 2D smart MRFs in the longitudinal direction, as shown in Fig. 9. Welded steel (iHEA) columns, as shown in Fig. 10, and IPE beams are used to design columns and beams, respectively. Column bases are pinned. The design gravity loads are applied at each floor level. The MRF prototype has a symmetrical configuration at each story level. Steel grade S460 (F_y = 460 MPa, F_u = 540 MPa), E = 21,000 MPa and v = 0.30 are used. The effect of high strain rate on the steel members and NiTi SMA bolts

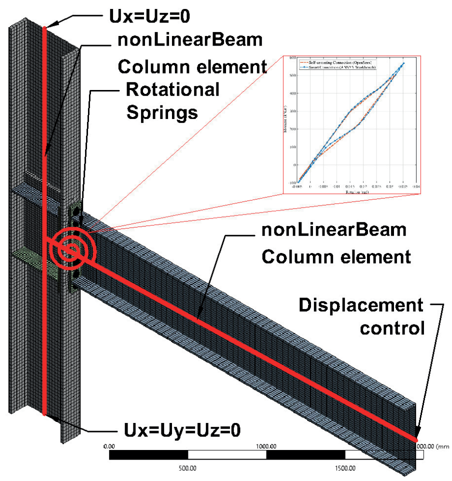

Fig. 8 Fully detailed FEM connection configuration and simplified model (red color)

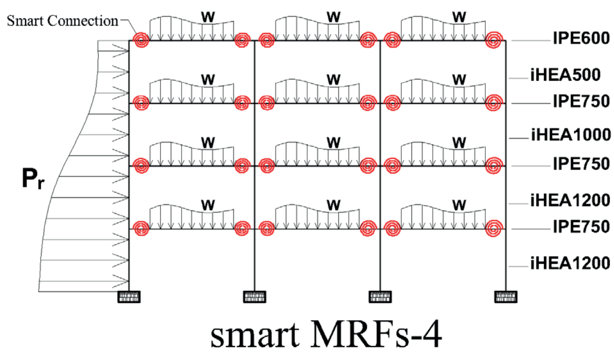

Fig. 9 MRF prototype

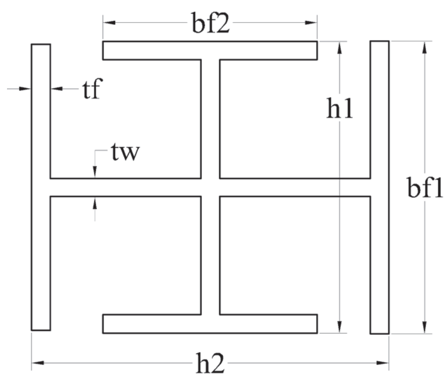

Fig. 10 Welded iHEA column profile

is considered. The prototype model is checked against Ultimate Limit State (ULS) and designed as a blast-protective structure [35].

2D Non-Linear Time History Analysis (NLTHA) has been performed on the prototype building using a nonlinear finite element program, Open System for Earthquake Engineering Simulation (OpenSees) [31]. More details of the numerical model are given in [35].

5 Reliability assessment

Using the proposed reliability framework approach, in the 1st Step, 350 sample points are generated considering the set of random variables. The sample points of the random variables are divided into three groups. The first group is W_{user} and W_{NEQ} which are used to model the blast loading profile. The second group is the uncertain parameters related to the material strength and gravity loads. The third group is the columns' resistance uncertain parameters (N_{yRk}, M_{yRk}). The influence of the correlation between the axial and moment interaction in the column, between columns at the same story level, and between the column of different story levels are investigated. Since the proposed Eurocode complying key design rules avoid column failure, the influence of the correlation is found to be very small, and it is therefore neglected. Later, all the random uncertain parameters are collected, classified, and recorded in a database. The 2nd Step starts with reading the data from the database and using them in the numerical analysis conducted by OpenSees. Following 350 numerical simulations, the numerical results, demand axial and moment in the columns, demand smart connection rotation (θ), and demand Inter-Story Drift Ration (ISDR) are stored in the designated database. Considering the plot fitting data analysis, the demand outcome data sets are fitted, and the relevant statistical parameters (μ, σ) are obtained. Using the MCS-LHS and obtained statistical parameters, the demand outcome data sets are redistributed. 10,000 new sample points are generated and stored in the designated database. It's worth mentioning that at this stage, each sample point represents the set of outcomes of the numerical analysis.

The post-blast analysis is conducted to detect the damaged component. A damage detection algorithm is proposed to search and visit every structural component and check if the components are failed. Using the performance function ($g_1(My, N)$), the induced bending and axial compression of the columns are first obtained from the redistribution and compared with its bending and axial force capacity distribution for each story level. If the column fails in the first story, the algorithm stops and considers the structure collapsed. The column failure for each single sample point iteration is counted and accumulated to find the Reliability Index (β). The second task of the damage detection algorithm is to check all the connections at every story level. In the performance function ($g_2(\theta)$), three hazard levels are used, Immediate Occupancy (IO), Life Safety (LS), and Collapse Prevention (CP). When the algorithm triggers a single connection failure, it stops and counts the failures. The final check is the Inter-Story Drift Ratio (ISDR) using ($g_2(ISDR)$). Similarly, three damage levels are introduced, namely Immediate Occupancy (IO), Life Safety (LS), and Collapse Prevention (CP). The algorithm determines the ISDR of each story level and compares it with the defined thresholds. The algorithm stops when the demanding ISDR is greater than the capacity.

Following the post-blast analysis, the Reliability Index (β) of the 4 story 2D MRF is obtained and assessed based on the target reliability index criteria by the JCSS [32] and ISO 2394 [33].

5.1 Random variables

The variability of blast load, dead loads, live loads, the columns' cross-sectional dimension, and structural member material properties are considered (see Table 1).

The uncertainties related to explosive mass are assumed based on two principal factors, W_{user} and W_{NEQ}. W_{user} is the human error factor related to the variation of the desired mass of the explosion. W_{NEQ} is a factor related to the variation of volume and/or mass of the explosion due to manufacturing error.

The mass model used in the probabilistic blast analysis is:

$$W = W_{nom} \times W_{user} \times W_{NEQ} , \tag{7}$$

where W_{nom} is the nominal mass or desired explosive mass.

The dead load acting on the structure consists of the mass of steel and concrete. The dead load is modeled as normal distribution through the variability of the unit weight. Following Bruce Ellingwood [38], the live load of the floors is modeled as extreme-I distribution. Similarly, the live load acting on the roof of the structure is modeled as Extreme-I with a mean value of 0.8 kN/m^2 and COV of 0.6.

The effect of variability of the columns' cross-sectional profile is included. Based on the JCSS [32], the columns' cross-sectional properties are modeled as a normal distribution with appropriate variance. Table 1 [12, 32, 36, 37] shows the random variables of three different cold-formed column cross-sections, iHEA 1200, iHEA 1000, and iHEA 500, used in the first, second, third, and fourth stories.

5.2 Reliability of the proposed smart structure subjected to blast loading

The proposed smart structure is subjected to an intentional explosion produced by Vehicle Borne Improvised Explosive Device VBIED. The blast peak reflected overpressure and other blast parameters originating from 1900 kg of Trinitrotoluene (TNT) from a 5.5 m distance from the front face of the structure. Based on the uncertain parameters in Table 1, 350 sample points are generated in the 1st Step using MCS-LHS.

As presented in Figs. 1–3, the reliability assessment started with providing the input variables to the demand and resistance model to generate the data distribution. For the demand model, after the detonation occurrence, the blast reflected overpressure is applied on the front face of the structure. Following the completion of the numerical simulation, the structural responses are measured. Simultaneously, the input parameters for the resistance model are generated. It is worth mentioning that the column's bending and axial compression capacity are calculated based on the current distribution and redistributed again, considering the correlation effect. The resistance model parameters are then used in the performance function.

The damage detection algorithm described above is used to find the defects in the columns, beam-to-column connections, and global stability of the structure (ISDR). The structure is considered failed when any failure condition in the relevant limit state functions is met. Using the random variables in Table 1 and the reliability approach discussed in Section 5, the target Reliability Index (β) is calculated.

The proposed smart structure is designed conforming to Eurocode-complying key design rules deterministically; therefore, the probabilistic outcome is expected to be aligned with the reasonable safety level of the international standard specification of the probabilistic models. The expected value of β is 3.3 for a 50 years reference period and the first reliability class (RC1). With 10,000 sample points used in the 2nd Step approach, the reliability index of the reference model is obtained, as shown in Table 2. The minimum value of β of global buckling of the columns ($g_1(My, N)$), CP of rotation, and CP of ISDR is 3.43. This value corresponds to Ultimate Limit State (ULS). Thus, the value of β satisfies the JCSS and ISO2394 requirements, and the target reliability index is achieved.

Table 1 Random variable used in reliability assessment of reference model

Parameter	Mean	COV	Distribution	Refs.
Blast load				
User factor (W_{user})	1.0	0.102	Normal	[12] [37]
NEQ factor (W_{NEQ})	(0, 0.82, 1.15)		Triangle	[12] [37]
Standoff distance(m)	5.5		Deterministic	
Dead load (kN/m^3)				
Unit weight of concrete	25	0.1	Normal	[32]
Unit weight of steel	78.5	0.05	Normal	[32]
Material properties (MPa)				
Yield strength of steel	460	0.1	Lognormal	
Live load (kN/m^2)				
Floors	4.8	0.6	Extreme-I	[36]
Roof	0.8	0.6	Extreme-I	-
Column cross-section (mm)				
iHEA1200: Length of flange (b_{f1})	700	0.03	Normal	
iHEA1200: Length of flange (b_{f2})	800	0.03	Normal	
iHEA1200: Length of web (h_1)	1200	0.03	Normal	
iHEA1200: Length of web (h_2)	700	0.03	Normal	
iHEA1200: Flange thickness (t_f)	36	0.03	Normal	
iHEA1200: Web thickness (t_w)	36	0.03	Normal	
iHEA1000: Length of flange (b_{f1})	500	0.03	Normal	
iHEA1000: Length of flange (b_{f2})	600	0.03	Normal	
iHEA1000: Length of web (h_1)	1000	0.03	Normal	
iHEA1000: Length of web (h_2)	600	0.03	Normal	[32]
iHEA1000: Flange thickness (t_f)	30	0.03	Normal	
iHEA1000: Web thickness (t_w)	30	0.03	Normal	
iHEA500: Length of flange (b_{f1})	400	0.03	Normal	
iHEA500: Length of flange (b_{f2})	303.6	0.03	Normal	
iHEA500: Length of web (h_1)	500	0.03	Normal	
iHEA500: Length of web (h_2)	400	0.03	Normal	
iHEA500: Flange thickness (t_f)	26	0.03	Normal	
iHEA500: Web thickness (t_w)	26	0.03	Normal	

Table 2 Reliability index (β) of reference model

Limit state functions	$g_1(My, N)$	$g_1(\theta)$			$g_1(ISDR)$		
		IO	LS	CP	IO	LS	CP
Reliability Index (β)	3.43	2.63	3.23	3.43	2.34	3.12	3.54

Therefore, the proposed reliability framework approach developed in this study verifies the deterministic design methodology. Furthermore, the approach can be used as an efficient assessment tool to evaluate the safety level of the smart MRF structures against blast loads. Finally, the approach is also intended to be used to perform a comprehensive reliability analysis on different smart structural configurations, covering more uncertain parameters.

5.3 Sensitivity analysis

The sensitivity analysis is conducted by using a range of Coefficient of Variation (COV) (see Table 3). The variability of W_{user} and W_{NEQ} are considered simultaneously, as presented in Eq. (7). For each value of COV, the sample points in the 1st Step and 2nd Step are generated to obtain the β value considering the limit state function and its hazard levels (if any). The proposed reliability framework is adapted for sensitivity analysis. The sensitivity of the Reliability Index (β) to all the uncertain parameters is computed for the current blast scenario. The sensitivity of β value to the uncertain parameters is first studied, and only the result of the most sensitive parameters is presented in this paper. The sensitivity of β to the uncertain parameters, W_{user} and W_{NEQ}, the vertical gravity loads, column profile cross-section, and tensile strength of steel (F_y) are investigated. However, the results of the most sensitive parameters are presented in this section. All other parameters are considered probabilistic, and their statistical properties are remained the same as the reference models (see Table 1).

The blast events attached with a very low probability of occurrence - high consequence. Consequently, the value of β is very high. Playing with the β value at a very high level to observe the sensitivity of the uncertain parameters requires an efficient reliability approach. For this purpose, the proposed reliability framework approach is considered efficient, as can be seen in the following paragraphs.

Fig. 11 shows the sensitivity of the structural reliability index to the W_{user} and W_{NEQ}. The global stability and connection rotation of the IO hazard level are the most sensitive to the charge weight. The similar reliability index of column buckling and $\beta_{Drift\text{-}LS}$ indicates the governing of both limit state when the data variability is further increased. However, for the same hazard level, the β of connection rotation is less sensitive to the charge weight variation. It is worth mentioning that the high variability of the charge weight leads to a noticeable decrease in the β vlaue. From the literature, it is evident that the uncertainty attached to the explosive material is very high; therefore, it is viable to have a very high COV which leads to a very low β.

The sensitivity of β to the material strength (F_y) is also shown in Fig. 12. The global stability of the structure is the most sensitive parameter to the material strength (F_y). However, the connection rotation is seen as less sensitive to the F_y. Although, the column buckling is the governing failure mode, but it is not sensitive to data variability. This is mainly because the column failure is not the governing failure mode.

Table 3 A range of COV for sensitivity analysis

Parameters	Range of COV		
Length of flange (b_{f1})	0.0%	5.0%	10%
Length of flange (b_{f2})	0.0%	5.0%	10%
Length of web (h_1)	0.0%	5.0%	10%
Length of web (h_2)	0.0%	5.0%	10%
Web thickness (t_w)	0.0%	5.0%	10%
Flange thickness (t_f)	0.0%	5.0%	10%
Gravity Loads			
Live Load (LL)	0.0%	40%	80%
Unit Weight of Steel (γ)	0.0%	5.0%	10%
Density of Concrete (ρ)	0.0%	5.0%	10%
Tensile strength of steel (F_y)	0.0%	7.5%	15%
Charge Weight	Case 1	Case 2	Case 3
W_{user} factor	0.0%	7.5%	15%
W_{NEQ} factor	0	0.41	0.82

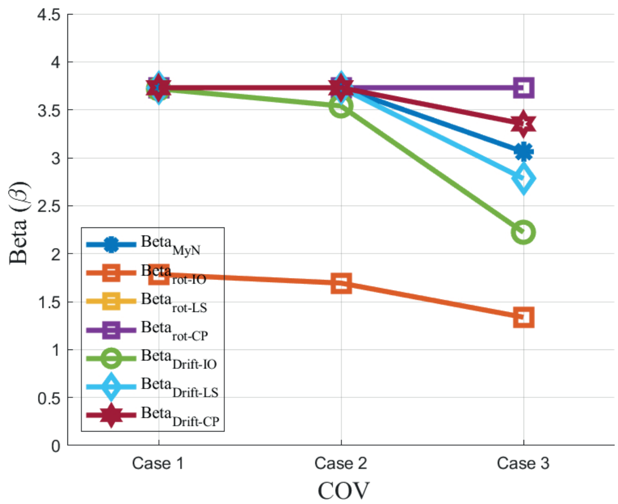

Fig. 11 Sensitivity of β to Wuser and WNEQ

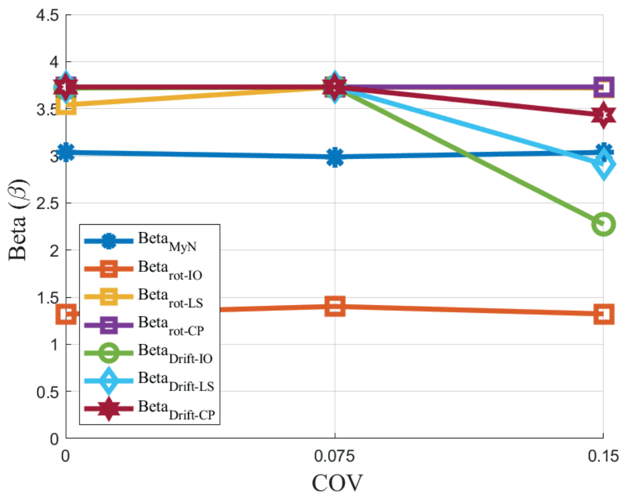

Fig. 12 Sensitivity of β to material strength (F_y)

The results from the sensitivity analysis show that the structure is noticeably sensitive to explosive charge weights and material strength. The developed reliability approach successfully captured the sensitive uncertain parameters of smart structures subjected to blast loading. Finally, encouraged by this result, the authors begin working on adapting the proposed reliability framework in comprehensive sensitivity analysis of the different configurations of the smart-MRFs structure. The detailed results of the structural analysis probabilistic-based study will be published in another paper.

6 Conclusions

This study proposes a reliability-based assessment framework of steel MRF equipped with NiTi SMA connections subjected to blast loads. Two-step approach is employed to measure the reliability index (β) of the smart structure. The Monte Carlo Simulation Latin Hypercube Sampling (MCS-LHS) approach generates random variables. The data sampling approach and the reliability algorithm is validated against Monte Carlo Simulation (MCS) and First Order Reliability Method (FROM). The blast load, dead load, live load, material strength, and column cross-sectional profile are considered to be the main uncertain parameters. The probabilistic model assesses the structural performance by three performance functions: column global buckling, rotation at the connections, and global stability of the structure (ISDR). Three hazard levels for connection rotation and global stability are included. Considering the complying Eurocode key design procedures proposed by the authors previously and using the Life Safety (LS) hazard level, which corresponds to the ultimate limit state function, the target reliability index is achieved. The results of the reliability analysis verified the efficiency of the proposed reliability approach. The sensitivity analysis is also performed, and the sensitivity of blast loads, material strength, and column web thickness is obtained. Material strength and explosive charge weight are considered the most sensitive uncertain parameters. To this end, the proposed reliability framework approach successfully predicted the associated risk of smart structure collapse. Accordingly, the smart MRF safety level can be assessed.

The proposed probabilistic approach is intended to develop a blast protective structure that can be used to indicate effective protective measures.

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