Smart MRF Structural Performance Evaluation Under Seismic Followed by Blast Loading Scenario

Sardasht S. Weli

Department of Civil Engineering, Komar University of Science and Technology, Sulaimany, 46001, Iraq
serdesht@gmail.com

Abstract. This study assessed the effectiveness of smart Steel Moment-Resisting Frame structures (MRFs) featuring Nickel-Titanium Shape-Memory Alloy (NiTi SMA) connection systems under the impact of multi-hazard blast-triggered seismic loading scenario. The NiTi SMA-based connection is designed conforming to the proposed complying key-design procedures proposed by the authors in the previous study. The connection response to the cyclic loading conditions is employed in the steel MRFs, hereafter called smart steel MRFs. A methodology for applying the blast-triggered seismic scenario is presented and applied to the smart steel MRFs by using the time history non-linear analysis. The structural response is evaluated for the blast-triggered seismic performance. A reference model is prepared with steel bolted rigid connections to highlight the role of the NiTi SMA-based connections in reducing the damages occurred due to the blast-triggered seismic events. The results show that the proposed Eurocode-complying key design procedures is considerably efficient to improve the stability of the structure.

Keywords: Blast-triggered seismic, NiTi SMA-based Connection, Smart Steel MRF, Key Design Rules, Steel MRFs

1 Introduction

Petrochemical building facilities are vital to modern industry society, yet these structures are inherently exposed to damage from accidental and intentional explosions. In regions with high seismicity, protecting these critical structures requires multi-hazard structural assessment and evaluation. Blast-triggered seismic (sequence loadings) is increased in the recent years, due to the technological industry demands on oil/gas energy sources. Using Liquified Petroleum Gas (LPG) is a common feature in petrochemical industry. Thus, explosions due to LPG storages and vessels triggered by seismic activity rises a huge risk of building collapse. Nonetheless, exploring the potential of self-centering devices as a novel approach leads to an opportunity to minimize the risk of multi-hazard loading scenarios.

Conservatively, the global response of the structure under blast loading scenarios are not considered in the assessment process. Thus, it’s been convinced that evaluating the local element response is satisfied [1]. On the other hand, global performance evaluation of structures subjected to seismic loading scenarios is very common. Although, both forces affect both global and element level of the structures. To minimize the extent of damage due to intentional and accidental explosions, some physical barrier measurements can be introduced, e.g., in case of terrorist acts. However, occurrence of some natural disasters shown that the most critical scenarios are hazard chains [2], where first the structure experience certain damage from the first hazard and the subsequent hazard is triggered by the first hazard. In hazard chain (multi-hazard) scenarios, there are multiple consequences affect the structures [3], which are, first, structural performance is further weakening in the subsequent loading case [4]. Second, the first hazard triggers the subsequent hazard, such as the case of strong ground motion damages LPG storages in petrochemical facilities. Consequently, explosion-induced seismic occur [5]. This is mainly due to the rupture of LPG container due to mechanical damages where LPG is held above its atmospheric pressure boiling point. The explosion, thus, occurs because of vaporization of a large fraction of the LPG, this phenomenon is called Boiling-Liquid Expanding-Vapor Explosion ‘BLEVE’ [6].

In recent years, employing self-centering connection has been introduced into the research and industry communities to avoid post-seismic [7–9] and post-blast [10–12] structural damages. Steel Moment Resisting Frames (MRFs) are equipped with self-centering devices to eliminate the residual deformation induced after seismic or blast loadings were occurred. The recentering capacity of these devices is the main cause of developing free-damage structures [13–16]. Nickle Titanium Shape Memory Alloy (NiTi SMA) has been extensively used in the design of self-centering connection in the seismic applications [17-18]. However, its use in the blast application is limited to very few studies conducted by the author of this study, [19-20]. Although, the self-centering devices are widely used, one can see very little efforts to address comprehensive design procedures in the codified body of structural engineering standards. Few studies have been conducted to set some key design rules. Weli et al, (2022) performed blast reliability analysis using NiTi SMA-based connection to mitigate the induced energy from intentional explosions [20-21].

This study aims at using the developed NiTi SMA-based connections subjected to multi-hazard loading scenarios following the proposed key design procedures in the previous studies by the authors of this study. The NiTi SMA-based connections are used in the MRFs which is used as a petrochemical facility, hereafter known as smart MRFs. The smart MRFs is initially exposed to a ground motion acceleration. The earthquake shaking produces mechanical damage in the nearby LPG container. The mechanical damage of the LPG container initiates BLEVE and then explosion. A methodology is proposed to model multi-hazard loading profile, and post multi-hazard structural risk assessment.

2 Multi-hazard loading

Multi-hazard events of petrochemical facilities are more frequent nowadays, as a consequence of commercial demands on explosive liquids. These events include sudden release of hazardous materials, e.g., LPG due to the mechanical damages to the LPG containers following strong earthquakes. The sudden release of these materials at a temperature above its atmospheric pressure is called BLEVE.

BLEVE is originated from a sudden release of confined liquid at a temperature above its atmospheric pressure boiling point. A fraction of the liquid vaporizes and a cloud of vapor and mist is produced which is accompanied with a blast effect. One of the main causes of BLEVE is mechanical damage due to external forces, e.g., during earthquake. Richard W. Prugh (1991) proposed an analytical approach to quantify the BLEVE into Trinitro Toluene (TNT) equivalent explosive charge weight [22]. In this study, Liquified Petroleum Gas (LPG) was used to generate the blast loading effect. LPG has main two components, namely Propane and Butane, in a range of mixture. Hungary LPG compound mixture is used as a case study, in which a percentage of Propane: Butane of 35:65 is used. The energy released due to a quick volume expansion can be found by this expression:

$$E = \frac{PV}{k-1}\left[1-\left(\frac{101}{P}\right)^{\frac{(k-1)}{k}}\right] kPa.m^3 \tag{1}$$

where k is the specific heat ratio. The above expression can be converted to kilograms of TNT as following:

$$W_{TNT} = \frac{2.4x10^{-4}PV}{k-1}\left[1-\left(\frac{101}{P}\right)^{\frac{k-1}{k}}\right] kg \tag{2}$$

Considering the LPG as an inert and the volume of vapor space and the pressure at rupture, the liquified vapor would flash. Corresponding to the weight of liquid at a flash point, the total volume can be calculated as following:

$$W_{TNT} = \frac{2.4x10^{-4}PV^*}{k-1}\left[1-\left(\frac{101}{P}\right)^{\frac{k-1}{k}}\right] kg \tag{3}$$

where V^* is given by:

$$V^* = V_T + W_L\left[\left(\frac{f}{D_V}\right)-\left(\frac{1}{D_L}\right)\right] m^3 \tag{4}$$

where V_T is the total volume of LPG tank (container), W_L is the weight of LPG in (kg), f is the flashing fraction, and D_L and D_V are the density of LPG compounds and saturated vapor at a temperature and pressure inside the tank at the time of rupture. The flashing fraction at the midway point between boiling point and critical temperature is calculated:

$$f = 1 - \exp\left[-\Omega\frac{C}{L}(T_C - T_b)\right] \text{ where } \Omega = 2.63\left(1-\left[\frac{T_C-T_O}{T_C-T_b}\right]^{0.38}\right) \tag{5}$$

where T_o, T_b, and T_c are initial, boiling, and critical temperature in (C^o), respectively. C is the average specific heat of the liquid (in $J/kg.K$) over the temperature interval T_o to T_b, and L is the average latent heat of vaporization over the interval temperature (in J/kg).

Regarding the seismic loading profile, a case study ground motion is selected from PEER database. The selection condition was based on the highest acceleration amplitude. For this purpose, Manjil-Abbar earthquake in Iran was selected with M = 7.37, which was occurred in 1990. The epicentral distance is 40.43km and PGA is 0.53g. Fig. 1 shows the time history acceleration ground motion of the selected seismic loading case profile.

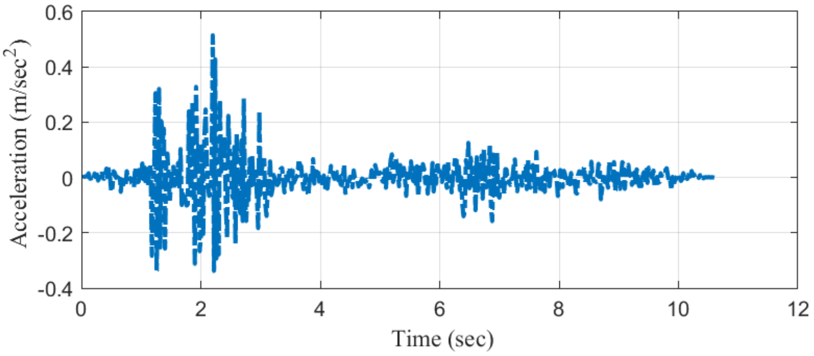


Fig. 1 Time history acceleration profile of Manjil-Abbar earthquake

By integrating both loading profile considering the timing of blast triggered incident, the multi-hazard loading profile is constructed (see Fig. 2). The proposed loading profile is applied onto the 2D smart MRFs.

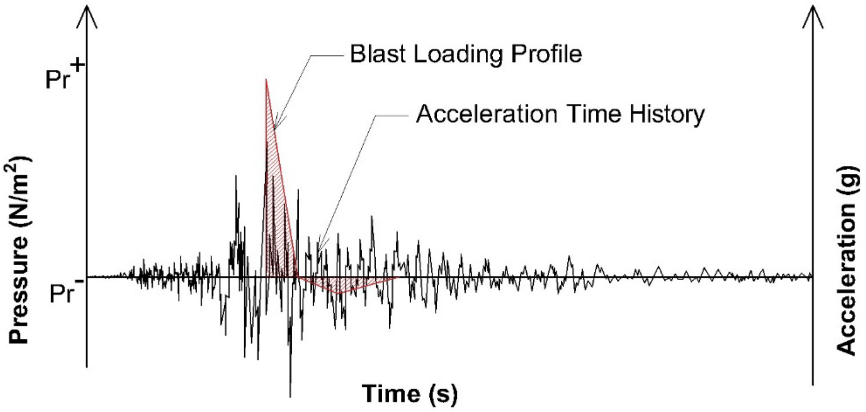


Fig. 2 Multi-hazard loading profile

3 Smart MRFs model

The smart MRF is steel MRFs equipped with NiTi SMA-based connections which are developed by the authors in [23]. The connections are designed based on the proposed key design rules which was developed by the authors previously, these key design rules provide hysteresis behavior to resist the applied blast loading. The proposed smart connections consist of column (HEA or iHEA), beam (IPE), end plate, backing plate, shear stiffeners, ribs, bolts, and nuts (as shown in Fig. 1a and b). The primary function of the smart connection is to eliminate or reduce irreversible inelastic deformation after the applied force is released. Thus, the structure returns to its original form through the connection re-centering capacity of the smart connections (see Fig. 3c). To further understand the key design methodology and the connection configuration, readers are referred to the author’s previous work.

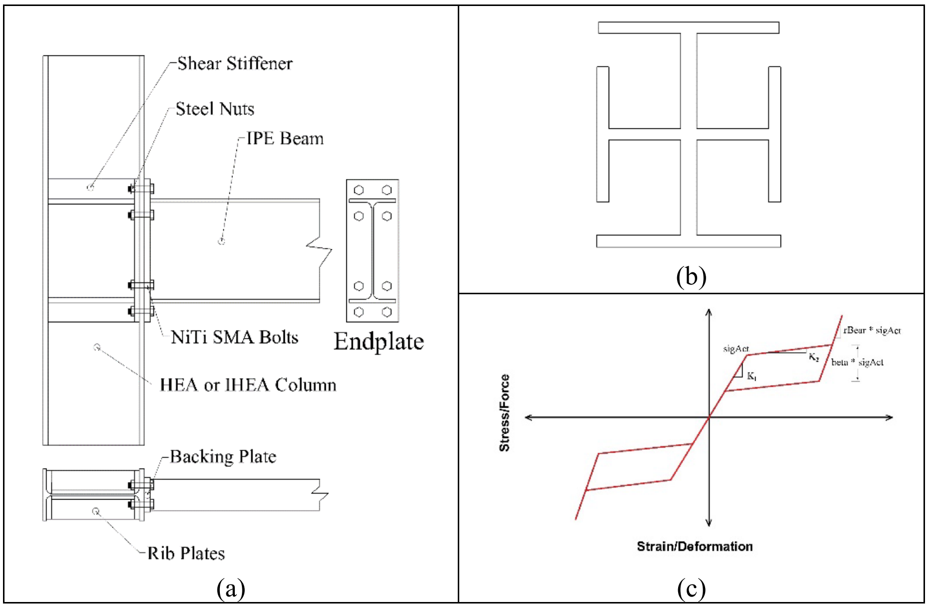
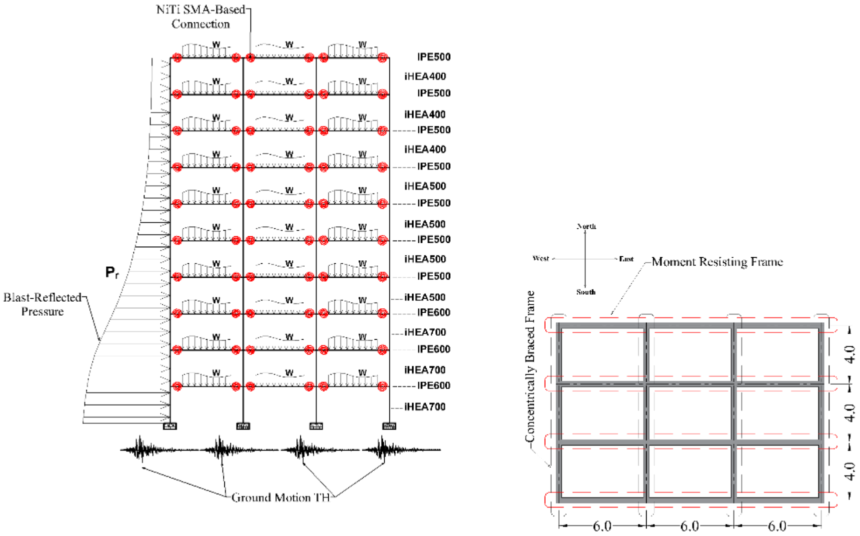


Fig. 3 (a) Smart connection configuration, (b) iHEA column profile, (c) NiTi SMA-based connection response

The proposed NiTi SMA-based connections are embedded into the steel MRF (see Fig. 4a). The smart MRF are used as a blast protective residential building with (6m) three smart MRFs spans in the longitudinal direction and (4m) three Braced Frames (BFs) spans (each 4m) in the transverse direction as shown in Fig. 4b. The focus of this study is only the smart 2D MRFs subjected to multi hazard loading profile.

Numerically, the proposed connection is modeled in two phases, first, the connection was modeled in full details in a general-purpose finite element software, ANSYS Workbench [24]. Second, since the fully detailed connection model is computationally expensive, the connection model is simplified into rotational spring elements. Open System for Earthquake Engineering Simulation (OpenSees) is used to idealize and simplify the connection model [25]. The rotational spring characteristics are applied onto zeroLength element from the OpenSees library. Using these zeroLength elements, two nodes with the similar coordinates are created at the beam to column joints. The influence of the panel zone is not involved and Stiff NonlinearBeamColumn element is used. Uniaxial SelfCentering material model is employed to simulate the hysteresis behavior of the zeroLength element rotational springs considering the self-centering material model developed by Haque et al. (2019)[26] and Tremblay et al. (2008) [27]. The idealized force-deformation relationship of the hysteresis system shown in Fig. 3c. The input parameters of the Uniaxial SelfCentering material are given in Table 1. For comparison, the smart connections are replaced by steel bolted rigid connections. The fully detailed steel rigid connection was modeled and simplified by bilinear rotational springs. Bilinear uniaxial material model is applied to the zeroLength elements to represent the steel rigid connections.



(a) (b)

Fig. 4 (a) smart MRFs, (b) Building layout

Table 1 Simplified smart connection parameters in OpenSees

Connection Model	K1	K2	sigAct	beta	escpBear	espSlip	rBear
IPE500	50,659	18,745	392	0.755	0.0177	0.0177	1.019
IPE600	102,312	48,588	736.02	1.016	0.019	0.019	0.996

K1(kN m/rad): Initial Stiffness
K2(kN m/rad): Post-Activation Stiffness
sigAct (kN m): Forward Activation Moment Force
epsSlip: Slip Connection Rotation
epsBear: Bearing Connection Rotation
rBear: Ratio of Bearing to Initial Stiffness
beta: Ratio of Forward to Reverse Activation Moment Force

The proposed multi-hazard simulation is implemented through a transient nonlinear time history analysis, which is performed by using Newmark method built-in in OpenSees. To generate structural modes, modal analysis is first conducted. Following that, the smart MRFs are subjected to the gravity analysis and dynamic time history multi-hazard analysis, respectively. Rayleigh damping is used. The next section presents the proposed methodology for the multi-hazard numerical analysis and its corresponding structural assessment.

4 Smart MRFs' multi-hazard evaluation methodology

The multi-hazard analysis started with feeding the proposed methodology by required information, e.g., level of structural performance, level of loading, and building layout. Fig. 5 shows multi-hazard evaluation methodology. The proposed methodology can be applied through 3 Tiers as followings:

1st Tier: The benchmark model is initiated with Building Information Modeling (BIM) and multi-hazard loading parameters. The BIM includes the numerical modeling descriptions, e.g., global level structure, system-connection model, building geometry, numerical analysis parameters, material modeling, and boundary condition.

The multi-hazard loading profile consists of two loading categories, namely seismic and blast loading profile. BLEVE methodology is used to quantify the LPG-TNT explosive charge weight. LPG container is used as a source of explosion. Using the methodology proposed in section 3, the equivalent TNT explosive charge weight and standoff distance are calculated. Modified Kingery Balmush Polynomial equations are used to generate LPG-based blast loading profile, the blast loading profile includes positive and negative reflected overpressure, rise time, and positive and negative duration [28]. The details of auto-framework reflected blast overpressure profile is discussed in [29]. Simultaneously, the ground motion time history is extracted from the PEER database. Multi-hazard loading profile is then created by integrating ground motion acceleration and blast reflected overpressure. Corresponding to the MCE, Life Safety (LS), and Collapse Prevention (CP) limit states, three seismic Intensity Levels (IL) are used. Finally, the building information modeling and loading scenarios profile are prepared for the second Tier.

2nd Tier: After completing the first tier of data and model preparation, the model is ready for analysis. This tier starts with modal analysis of the models. Eigen values and vectors are calculated which are later used to define the damping characteristics. Later, gravity analysis is applied, and the analysis time is set to zero to maintain the results of gravity analysis in effect. Following the gravity analysis, multi-hazard time history analysis is performed. The multi-hazard loading profile is applied through transient dynamic analysis. The blast load is applied after a short time following ground motion hit the foundation of the structure. The triggering time is set based on the highest amplitude of the ground motion acceleration.

3rd Tier: Post multi-hazard structural evaluation and assessment starts with storing the structural response in a designated database. The structural responses consist of time history displacement, Maximum Inter-Story Drift (MISD), and Residual Inter-Story Drift Ratio (RISDR). FEMA-P58 damage state criteria are used to assess the building performance. DS1, DS2, DS3, and DS4 are used to define the damage state of the proposed smart MRFs. The assessed results are compared with rigid steel MRFs.

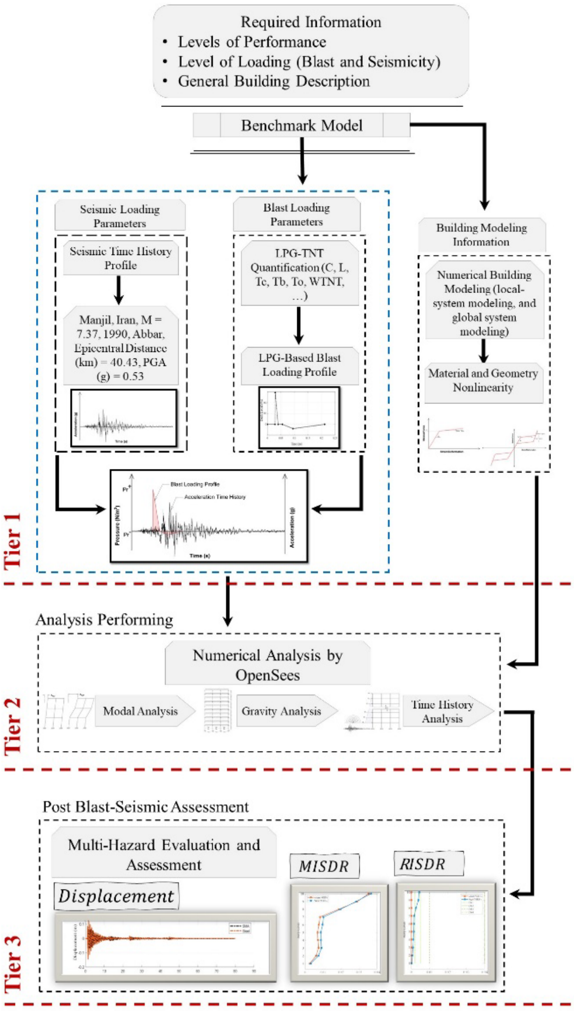


Fig. 5 Multi-hazard evaluation methodology

5 Multi-hazard evaluation and assessment of smart and steel MRFs

The described multi-hazard evaluation methodology is used to assess the structural integrity of smart MRFs subjected to blast-triggered seismic loading profile by means of dynamic transient analysis. Another purpose of the analysis is to evaluate the proposed Eurocode key design procedures developed by the authors to build blast-triggered seismic protective structures. Engineering structural performance measurement tools are used to evaluate the structural performance, namely displacement time history profile, MISDR, and RISDR.

Fig. 6 shows displacement time history profile. The response of both steel and smart MRFs experienced very close displacement during the 20 sec of the multi-hazard loading. It worths to mention that the highest displacement amplitude starts when the blast load applied.

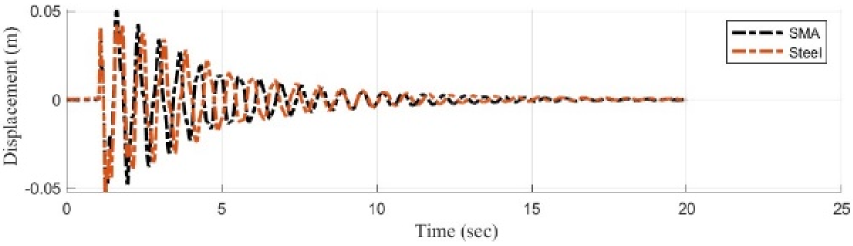
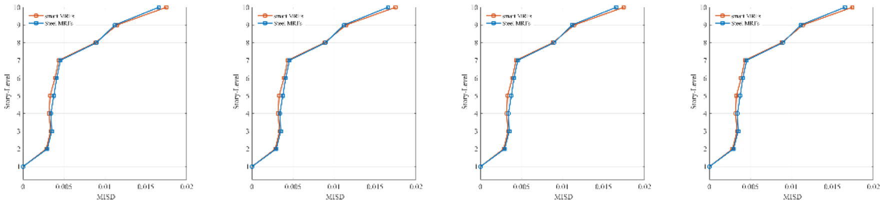


Fig. 6 Displacement time history response

To further explore the influence of both actions on the global response of the smart and steel MRFs, MRISD of both models are measured and evaluated (as shown in Fig. 7). Since the explosive charge weight is the governing failure mode, the effect of the seismic intensity level is invisible on the MISD. Therefore, the response of all the IL is identical.



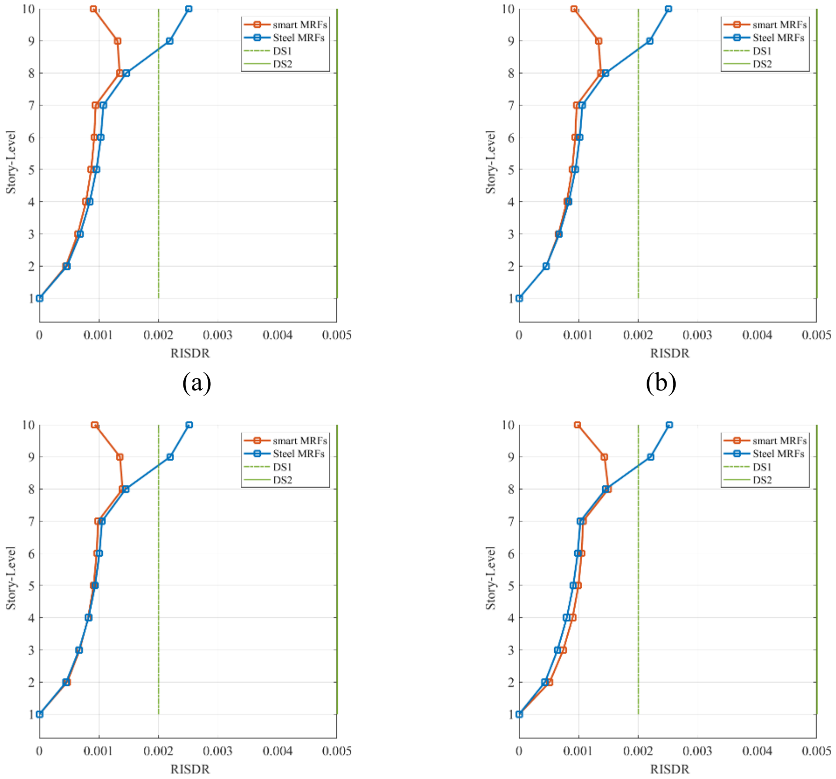
(a) (b) (c) (d)

Fig. 7 Maximum Inter-Story Drift MISD, (a) Normal IL = 1.0, (b) MCE IL = 1.5, (c) LS IL = 2, (d) CP IL = 4

The results were further assessed based on FEMA P-58 [30]. FEMA P-58 classified damage states into to four main stages based on RISDR, namely DS1, DS2, DS3, and DS4. DS1 and DS2 description can be found below:

- DS1, no structural element replacement is necessary when RISDR is less than 0.2%; however, nonstructural elements or mechanical components sensitive to building alignment may be replaced.
- When RISDR is more than 0.2% but less than 0.5%, DS2, "realignment of structural frame and related structural repairs required to maintain permissible drift limits for nonstructural and mechanical components and to limit degradation in structural stability."

Applying the codified structural assessment, Figs. 8(a-d) show that the Smart MRFs-can be classified as DS1; thus, no structural element replacement is necessary. For steel MRFs, structural realignment is possible with permissible drift range. It can be seen that the proposed smart MRFs and its key design procedure under multi-hazard threat are successfully reducing the RISD to its minimum value. However, the steel moment connection experience a considerable residual drift. The similar response of the steel MRFs is due to its irreversible deformation in the connection which was yielded under the explosion, therefore, with different IL of ground motion there is negligible change. Furthermore, the proposed multi-hazard structural assessment methodology is efficiently triggered the smart behavior of the connection models.



(a) (b)

(c) (d)

Fig. 8 Residual Inter-Story Drift Ratio RISDR, (a) Normal IL = 1.0, (b) MCE IL = 1.5, (c) LS IL = 2, (d) CP IL = 4

6 Conclusion

In this study, a multi hazard methodology is proposed to evaluate and assess smart and steel MRFs subjected to blast-triggered seismic multi hazard loading profile. The smart MRFs are designed based on several Eurocode-complying key design rules proposed by the authors in their previous research works. Following the structural analysis and evaluation, the below conclusions are made:

1. Innovative approaches to strengthen structural integrity under multi-hazard threats require an effective and simple methodology for engineering practices.

2. Steel MRFs equipped with NiTi SMA-based connections are seen effective in reducing residual deformation and consequently minimize the risk of collapse under multi-hazard threats. On the other hand, steel MRFs are left with considerable irreversible residual deformation.
3. Smart structures designed with recommendation from blast protective design methodology is proven to be efficient for structures subjected to multi-hazard threats.
4. More study is required to explore further the multi hazard analysis and propose a comprehensive methodology to assess the post multi-hazard structural performance.

References

1. Unified Facilities Criteria (UFC) (2014) Structures to Resist the Effects of Accidental. USA.
2. Petrini F, Gkoumas K, Rossi C, Bontempi F. (2020) Multi-Hazard Assessment of Bridges in Case of Hazard Chain: State of Play and Application to Vehicle-Pier Collision Followed by Fire. Front Built Environ 6:1-19. doi:10.3389/fbuil.2020.580854
3. Francioli M, Petrini F, Bontempi F. (2023) Structural robustness analysis of RC frames under seismic and blast chained loads scenarios. Journal of Building Engineering (67) 105970. doi:10.1016/j.jobe.2023.105970
4. Zaghi AE, Padgett JE, Bruneau M, et al. (2016) Establishing Common Nomenclature, Characterizing the Problem, and Identifying Future Opportunities in Multihazard Design. Journal of Structural Engineering 142(12):1-8. doi:10.1061/(asce)st.1943-541x.0001586
5. U.S. ARMY CORPS OF ENGINEERS. (2005) Unified Facility Criteria (UFC 3-340-02) Sturctures to Resist The Effects of Accidental Explosions, USA.
6. Prugh RW. (1991) Quantitative evaluation of “BLEVE” hazards. Journal of Fire Protection Engineering 3(1):9-24. doi:10.1177/104239159100300102
7. Shi F, Yuan W, Ozbulut OE, Zhang C, Zhou Y. (2024) Performance assessment of steel frame buildings with hybrid self-centering braces under extremely rare far-field earthquakes. Thin-Walled Structures 195:111456. doi:10.1016/j.tws.2023.111456
8. Yan X, Shu G, Rahgozar N, Alam MS. (2024) Seismic design and performance evaluation of hybrid braced frames having buckling-restrained braces and self-centering viscous energy-dissipative braces. J Constr Steel Res 213:108359. doi:10.1016/j.jcsr.2023.108359
9. Yan X, Shu G, Zhang R, Alam MS, Qin Y. (2024) Hysteretic and seismic performance of disc spring-based self-centering viscous dampers for improved seismic resilience. Eng Struct 300:1117161. doi:10.1016/j.engstruct.2023.117161
10. Weli SS, Gergely VL. (2020) Behaviour of Smart Steel Column-Beam Connection Under Blast Loading. In: Eurosteel. :9.

11. Weli SS, Gergely VL. (2021) Blast Performance Evaluation of Steel Moment Resisting Frame Equipped with Smart Bolted Connection. Journal of Performance Constructed Facility 35(5):04021050-04021051.
12. Weli SS, Vigh LG. (2022) Blast Performance of Steel Frames Equipped with NiTi SMA Bolts: Design Procedure and Numerical Evaluation. Journal of Structural Engineering 148(5):1-14. doi:10.1061/(asce)st.1943-541x.0003314
13. Kim HJ, Christopoulos C. (2009) Seismic design procedure and seismic response of post-tensioned self-centering steel frames. Earthq Eng Struct Dyn 38(3):355-376. doi:10.1002/eqe.859
14. Hameed J, Abbas AL. (2019) Seismic Performance of Two Story Steel Building Using Shape Memory Alloys (SMAs) Bars. Civil Engineering Journal 5(7):1465-1476. doi:10.28991/cej-2019-03091345
15. Sun G, Liu H, Liu W, Yang W. (2022) Development, simulation, and validation of sliding self-centering steel brace with NiTi SMA wires. Eng Struct 256:114069. doi:10.1016/j.engstruct.2022.114069
16. Wang W, Fang C, Liu J. (2017) Self-Centering Beam-to-Column Connections with Combined Superelastic SMA Bolts and Steel Angles. Journal of Structural Engineering (United States) 143(2):1-16. doi:10.1061/(ASCE)ST.1943-541X.0001675
17. Fanaiea N, Monfared MN. (2016) Cyclic behavior of extended end-plate connections with shape memory alloy bolts. Structural Engineering and Mechanics 60(3):507-527. doi:10.12989/sem.2016.60.3.507
18. Yam MCH, Fang C, Lam ACC, Zhang Y. (2015) Numerical study and practical design of beam-to-column connections with shape memory alloys. J Constr Steel Res.104:177-192. doi:10.1016/j.jcsr.2014.10.017
19. Weli SS, Gergely VL. (2021) Behaviour of Smart Steel Column-Beam Connection Under Blast Loading. Ce/Papers. 4(2-4):857–865.
20. Weli SS, Gergely VL. (2022) Blast reliability assessment, and sensitivity analysis of steel MRFs equipped with NiTi SMA bolts. Engineering Structures 286, 116137
21. Weli SS, Vigh LG. (2022) Reliability Assessment Methodology of Blast Protective Smart-Steel Structure. Periodica Polytechnica Civil Engineering 67 (3), 671-682.
22. Prugh RW. (1991) Quantitative evaluation of "BLEVE" hazards. Journal of Fire Protection Engineering. 3(1):9-24. doi:10.1177/104239159100300102
23. Weli SS, Vigh LG. (2022) Probabilistic Fragility Analysis of Smart Steel Moment-Resisting Frame Structure Subjected to Intentional Blast Loading.; Eurasian Conference on OpenSees, 362-376. doi:10.1007/978-3-031-30125-4
24. Ansys inc. (2017) ANSYS reference manual. Published online.
25. Mazzoni S, Mckenna F, Scott MH, Fenves GL, Iii A. (2007) Open System for Earthquake Engineering Simulation (OpenSees) OpenSees Command Language Manual.
26. Haque ABMR, Issa A, Shahria Alam M. (2019) Self-Centering Energy Dissipative Bracing System for the Seismic Resistance of Structures: Development

and Validation. J Intell Mater Syst Struct. 30(12):1823-1849. doi:10.1177/1045389X19844328

27. Tremblay, Robert and Lacerte, M and Christopoulos C. (2008) Seismic Response of Multistory Buildings with Self-Centering Energy Dissipative Steel Braces. Journal of Structural Engineering. 134(1):108-120. doi:10.1061/(ASCE)0733-9445(2008)134
28. Swisdak Jr MM. (1994) Simplified Kingery Airblast Calculations.
29. Weli SS, Vigh LG. (2022) Blast Performance of Steel Frames Equipped with NiTi SMA Bolts: Design Procedure and Numerical Evaluation. Journal of Structural Engineering. 148(5):1-14. doi:10.1061/(asce)st.1943-541x.0003314
30. FEMA. FEMA P-58-1(2018) Seismic Performance Assessment of Buildings. Volume 1 – Methodology. Vol 1.