Behaviour of Smart Steel Column-Beam Connection Under Blast Loading
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Abstract

The generated damages in steel structures due to terrorist attack explosion has attracted structural engineering communities, because the effect of blast loading is extremely sever and destructive. The behavior of Superelastic Nickle Titanium Shape Memory Alloy (NiTi SMA) beam-column connection was infrequently studied under the effect of blast loading. The present study develops smart steel beam-column connection under the effect of blast loading. The performance of the proposed connection configuration is evaluated numerically to make better understanding of the conceptual design of NiTi SMA-based smart bolted connections. NiTi SMA-based smart connection stiffness and strength is determined based on Eurocode steel joint design procedures. Analytically, Simplified Kingery Airblast Calculations approach is used to generate time history blast reflected overpressure parameters. The austenite effect of NiTi-SMA is introduced to the global 2D frame model by moment rotation capacity curves. The structural components are verified in Ultimate Limit State (ULS) by using the results of global 2D model. The outputs from the 2D global model is introduced in sub-numerical models. The sub-models examined by finite element software code. The result shows that the hysteresis flag-shaped loop of NiTi-SMA is well expressed by the sub-models’ numerical solutions. As a result, the proposed connection configuration can highlight the efficiency of NiTi-SMA in terms of energy dissipation capacity under blast loading successfully.

Keywords

Superelastic Nickle Titanium Shape Memory Alloy, NiTi SMA-based smart connection, blast loading, global analysis, numerical sub-models, energy dissipation capacity, high strain rate, basic design procedures, flag-shaped hysteresis loop

1 Introduction

Shape Memory Alloy (SMA) has shown its efficient potential to mitigate structural vibration since it has been discovered and used by [1], [2]. SMA has been widely used in the field of structural engineering to improve earthquake resistance. The multidisciplinary capacity of SMA has become the researcher’s attraction to be used as smart elements to improve energy dissipation capability. Bin et al. developed a steel column base connection which is equipped with NiTi SMA bolts, the bolts’ performance was investigated experimentally under cyclic load [3]. The study showed that joint configuration equipped with NiTi SMA bolts experienced a fully flag-shaped hysteresis loop. Recently, Gur et al. examined the effect of SMA bars to improve the seismic performance of steel frames equipped with SMA dampers [4]. The study observed the novelty of SMA comparing with other damper models, e.g., yielding damper.

Despite the promised self-centering, excellent damping, high energy dissipative characteristics of SMA, e.g., NiTi SMA, the material cost and fabrication process complication are still challenges at the scientific level.

It is well described, in the literature, that the application of SMA is quite promising under the effect of seismic and cyclic loading. However, the situation is extremely complex when it comes to the application of NiTi SMA-based smart material under the effect of high strain rate loading, e.g., blast loading. Therefore, the application of SMA based smart material is limited to the automotive industry. So far, no direct application of SMA under blast loading in civil engineering is found. The only SMA application exposed to blast loading is porous NiTi SMA which is first designed by [5]. Pant et al. performed a parametric study to investigate the phase transformation and energy dissipation capacity of porous SMA subjected to impact/blast loading [6].

Due to the similarities between the earthquake and explosion loading environment, the possibility of using SMA as self-centering devices to mitigate the blast loading impulse is considered efficient. However, the nature of blast loading is somehow different, for instance, an extreme high strain rate along with high pressure impulse follows the explosion events [7], while seismic loading possesses a lower strain rate and it is cyclic in nature.

Very few efforts have been conducted to elaborate dynamic
characteristics of SMA subjected to high strain rate. Generally speaking, the impact of the loading rate on the flag-shaped hysteresis loop of SMA is not straightforward. Xu et al. observed that the relationship between loading rate increment, the energy dissipation, and Equivalent Viscous Damping is disproportional [8]. This behaviour is well noticed by many researchers [9], [10],[11]. Hence, the influence of strain rate on the smart behaviour of SMA is critical and cannot be ignored. To give a clear view on the performance of SMA based smart material in an extremely high strain rate environment such as an explosion, an intensive literature review has been conducted and further discussion is presented.

The present study is an extension of the authors’ previous research work [12]. The previous study employed a modified nonlinear static analysis approach to assess the performance of smart beam-column moment resisting frame connection subjected to equivalent static blast overpressure analytically. The current study proposes a new designed connection configuration of the smart connection. Moreover, it performs dynamic transient analysis to examine the performance of NiTi SMA-based smart moment resisting frame connection numerically. The smart beam-column connection is designed based on Eurocode 3 [13]. The connections are designed analytically to incorporate the influence of NiTi SMA. The moment rotation capacity curve of the joint is used to provide semi-rigid/partial strength joint capacity to the global 2D frame. The structure is verified in the Ultimate Limit State (ULS) by using the results of the global 2D model. Based on the design calculation, an adequate beam, column, connection component sizes are proposed. Finally, Finite Element Analysis is also performed to evaluate the NiTi SMA-based smart connection at a very high strain rate transient loading.

2 Modeling of Blast Loading

The dynamic response of structures subjected to blast loads are complicated enough that simplifications in many aspects are a must. High loading rate, material nonlinearity, uncertainties in blast loads, etc. are all involved in the determination of blast loads. The simplification process requires some assumptions.

The effect of explosions on the structure can be shown by distributed dynamic loads perpendicular to the front facade of the target structure [14]. The blast wave pressure on the other faces and the roof is not considered. The horizontal load is a transient dynamic load over a very short period (positive and negative duration phases), but it may not maintain until the structure reaches its peak response. All the proposed approaches consider the computation of the scaled distance. The full discussion and the illustration charts are given by [15]. When the blast wave travels, incident blast overpressure, through space encircles all the bodies near the detonation sources. The interaction between the objects, structures, for instance, and the blast wave generates a pressure-time history pattern, as shown in Figure 1. The blast reflected overpressure is much higher than the incident blast overpressure. It is assumed that the structure experience no or negligible damage after the positive phase duration, as a result the negative phase is ignored.

The blast overpressure and the positive phase duration are determined by the Simplified Kingery Airblast Calculations approach by Michael M. Swisdak [16]. The Simplified Kingery approach presents the same result as the Kingery polynomial equation result [17]. The accuracy of the simplified approach is within 1% in comparison with the original Kingery results. Simplified Kingery Airblast Calculations approach recommended the following polynomial equation to determine the blast wave parameters,

\[
Y = EXP(A + B \times (\ln(Z)) + C \times (\ln(Z))^2 + D \times (\ln(Z))^3 + E \times (\ln(Z))^4 + F \times (\ln(Z))^5 + G \times (\ln(Z))^6)
\]

\[
Z = \frac{R}{W^{1.5}}
\]

where \(Y\) is the polynomial function of blast reflected overpressure \(P_r\) and positive phase duration \(t_p\). \(A, B, C, D, E, F, G\) are the coefficients of the polynomial curves. \(Z\) is scaled distance, \(R\) is standoff distance from the object to the center of detonation, and \(W\) is the equivalent charge weight of TNT. The current model consists of 400kg of TNT detonates at 15m from the front façade of the structure, as shown in Figure 2.

3 Design of SMA-based Smart Connection

3.1 Design of joints according to Eurocode 3
The SMA-based smart joint is designed according to Eurocode 3 [13]. To incorporate the effect of SMA bolts, the connection design has been conducted analytically. The mechanical and geometrical properties of the connection components are shown in Table 1. Eurocode 3 classifies the endplate mode failure into three modes,

1. Complete yielding of the flange
2. Bolt failure with yielding of the flange
3. Bolt failure

It is of importance to ensure that the bolts failure is the governing failure mode of the connection since the SMA bolts are responsible for providing hysteresis behaviour. To optimize the joint design, two groups of connections are proposed. The first group (Group 1) is used in the first bottom three storeys (Group 1) and the second group (Group 2) is designed for the rest of the storeys in the following global 2D frame model analysis.

The mechanical properties of SMA bolts reported by [19] are adopted in this study, as shown in Table 2.

Figure 3 shows the design configuration of both groups. Both connection groups have different design configurations. Any deformation occurring in the other components of the connection affects the contribution of SMA bolts on the overall behaviour of the connection. Lateral shear stiffeners are provided to support the column web and flange resistance. The inclined stiffeners are the key components of the joint classification to design semi rigid and partially strength joints. This type of connection design requires additional attention in order to determine optimal design values. The welding part connection is not studied here, and it is out of the scope of this paper. Flexible components may alter the efficiency of the SMA bolts; therefore, extra attention is necessary.

| Component | Steel Type | Group No. | Cross section |
|------------|------------|-----------|---------------|
| Beams      | S235       | 1         | IPE400        |
|            |            | 2         | IPE500        |
| Columns    | S235       | 1         | HEA500        |
|            |            | 2         | HEA400        |
| Bolts      | SMA        | -         | -             |
| End Plate  | S235       | 1         | (200x600x23) mm |
|            |            | 2         | (200x500x23) mm |
| Stiffeners | S235       | 1         | (100x10) mm   |
|            |            | 2         | (90x10) mm    |

Table 2 Mechanical Properties of SMA bolts

| $\sigma_{Ms}$ | $\sigma_{Mf}$ | $\sigma_{As}$ | $\sigma_{Af}$ | $\sigma_{EF}$ | $\epsilon_L$ |
|---------------|--------------|--------------|--------------|--------------|-------------|
| 380MPa        | 490MPa       | 220MPa       | 120MPa       | 50GPa        | 0.05        |

Figure 3 SMA-based smart connection, (a) Group 1 and, (b) Group 2

3.2 Effect of Strain Rate

By nature, blast loading is high strain rate loading. The NiTi SMA-based smart connection strongly depends on the loading rate in terms of energy dissipation capacity and re-centering capability. An intensive literature review has been conducted to make a clear understanding of the effect of a high loading rate on the SMA bolts. It is confirmed that the flag-shaped hysteresis loop of the SMA material can be seen up to 1000s$^{-1}$. Many researchers, [9],[11],[20],[21],[22],[23],[24],[25],[26],[27],[28], studied the behaviour of SMA under low, medium, and high strain rates. The presented studies show that the range of strain rate for which the SMA maintains its energy dissipation capacity characteristics is up to 1000s$^{-1}$.

The strain rate of the proposed joint configuration is calculated based on the initial stiffness, the moment rotation capacity and the applied loading velocity. The strain rate of the Group 1 and Group 2 connections are 458s$^{-1}$ and 470s$^{-1}$ respectively. The obtained strain rate is below 1000s$^{-1}$. Therefore, the hysteresis behaviour of the NiTi SMA-based smart connection in the FEM model is expected.

When the explosion occurs, the blast overpressure requires some milliseconds to reach the front face of the structure and some other few milliseconds to rise to its peak value. The rise time of blast overpressure is used to determine the strain rate of the SMA bolts. The available empirical blast overpressure equations are not capable of measuring the rise time [7]. For this purpose, the rise time is observed from the recent explosion experiments that are used (See Table 3). The rise time is selected based on the scaled distance.

| Author(s)                | Scaled Distance ($\frac{m}{kg^2}$) | Rise Time, $t_o$ (ms) |
|--------------------------|-----------------------------------|-----------------------|
| Xu-dong Zhi et al. [29]  | 3.4                               | 0.0628                |
| Omar Algassem et al. [30]| 5.5                               | 0.559                 |
| B. Luccioni et al. [31]  | 12.9                              | 0.212                 |
| Yan Liu et al. [32]      | 0.98                              | 0.009                 |
| Ji-Hun Choi et al. [33]  | 0.51                              | 0.00257               |
4 Simplified Structural Design

The simplified model consists of 10 storeys with 3m height and 6m bay width. The columns and beams are designed according to Eurocode 3. The AxisVM software is used to model the 2D frame structure [34]. The applied load is equivalent static blast reflected overpressure. The geometrical and material properties of the columns and beams are given in Table 1. The equivalent static blast reflected overpressure is decreasing along with the height of the structure as the scaled distance is increasing.

The joint capacity is defined by two moment rotational curves. The effect of the austenite phase of the super-elastic SMA is considered. The input parameters are used as spring characteristics for rotation. The beam end release characteristic of the lower three storeys are defined by the parameters in Figure 4. The remained end beam release characteristics are defined by parameters in Figure 5. The end beam releases, denoted by closed blue circles, are defined at the end of the beams (see Figure 6).

The verification of structural components is performed in the Ultimate Limit State (ULS) by using the results of the global 2D model. Few iterations are required to obtain an optimal component size to maintain the structure stable. At this point, the idea of two groups of connections is raised. The output of the global 2D frame analysis is used to create finite element models and evaluate the energy dissipation capacity of the joints subjected to transient moment, shear, axial force, and surface dead and live load.

5 Finite Element Sub-Models

The hysteretic behaviour of the SMA-based smart connection is evaluated by applying the induced moment ($M_i$), shear ($V_x, V_y$), and axial load ($N_i$) generated from the 2D global model and applied live load ($W$). The forces are applied as an impulse load on the FEM sub-models. The transient loads, which are pressure impulse (P-I) diagram, is applied. Two load steps are applied, the first step time is ended at the end of the rise time ($t_r$), 0.0628ms, and the second step time is ended at the end of positive phase duration ($t_o$). The positive phase duration of the Group 1 and Group 2 connection is obtained as 15.1ms and 18.89ms, respectively. Group 1 and Group 2 NiTi SMA-based smart connections are located on the second and seventh floor, as indicated by red circles, see Figure 6. The blast overpressure time-history, the applied forces and the positive phase duration, vary for each sub-model (See Figure 7). Finite element code, Ansys Workbench software, is used to evaluate the proposed connection.

Element type SOLID187 and SOLID186 are used to model beam, column, endplate, stiffeners, bolts, and nuts. SOLID186 and SOLID187 are higher-order 3D 20-node and 10-node solids consecutively, the elements are defined by 20 and 10 nodes respectively, having three degrees of freedom per node: translations in the nodal x, y, and z directions. Both element types support plasticity, hyperelasticity, creep, stress stiffening, large deflection, and large strain capabilities. The contact and sliding between 3D target surfaces and deformable surfaces are defined by CONTA174. TARGE170 is used to represent various 3D surfaces for the associated contact elements.

Half beam and column are included in the sub-model analysis (See
The sub-models experience a very high loading rate. The moment, shear, axial force, and surface dead and live load reach their peak within micro milliseconds, then back to zero within a time step which is equivalent to the positive phase duration. The lower column end is fixed while the upper end is pinned with free displacement in X-direction. The applied forces are the moment at section A-A, shear forces at the upper column end and mid of the beam, axial force at the beam mid, and dead and live surface load on the beam.

**Figure 9** Group 1 SMA connection bolt failure

The Group 1 NiTi SMA-based smart connection failure is governing by the first bolt raw, as shown in Figure 9. Although extra care is taken to design for the third mode failure, considerable deformation was developed at the lower part of the beam web and flange, column web and flange, and the stiffeners (See Figure 11). For this reason, a fully flag-shaped hysteretic loop of moment rotation capacity curve of the system is not promising. Similarly, the Group 2 connection response to the applied transient moment, shear, axial force, and surface dead and live load is evaluated. The result shows that the failure mode is not pure bolt failure as some rigidity problem of the other part of the connection element was raised (See Figure 10 and Figure 12).
Figure 11 Group 1 SMA connection yield stress

Figure 13 and Figure 14 show the stress strain behaviour of the system. The hysteresis behaviour of the system can be seen. This is mainly due to the fact that the maximum stress and strain was developed in the bolts. It is confirmed that within the developed strain rate, 458s\(^{-1}\) and 470s\(^{-1}\), the connection system provides reasonable energy dissipation and recentering capacity with significantly low or zero residual stress.

Figure 12 Group 2 SMA connection yield stress

Figure 15 and Figure 16 depict the moment-rotation relationship of Group 1 and Group 2 connection systems, respectively. The moment-rotation capacity curves are obtained from the sub-models to illustrate the effect of NiTi-SMA based smart connection to recover the deformed shape to their original shape. Moreover, the considerable low residual deformation of both connection groups exhibits the novelty of the proposed connection configuration. More importantly, the connection configuration is relatively simple and effective in comparison to the existing connection configurations in the literature.

The enclosed area of the hysteresis curve represents the energy dissipation capacity. The enclosed area of the first connection group is almost the same as the area in the second connection group.

Figure 13 Group 1 connection stress-strain relation at a strain rate 458\(^{-1}\)

Figure 14 Group 2 connection stress-strain relation at a strain rate 470\(^{-1}\)

Figure 15 Group 1 connection force-deformation relationship

This phenomenon confirms the fact that both connection groups have the same energy dissipation capacity.
It can be concluded that the first and second failure mode of the endplate is strictly prohibiting the NiTi-SMA bolts from developing hysteresis behaviour. As a result, it is recommended to pay extra attention to the connection configuration during the early phase of the design procedures.

A comparison is made by replacing the NiTi-SMA bolts with conventional steel bolts class 6.8. For the purpose, connection Group 1 is selected. The analysis is conducted under the same condition as described in section 4. Figure 17 shows the stress-strain curve for both NiTi-SMA connection and steel connection. The residual strain of the steel bolts is 2.5%, while the NiTi-SMA bolts experience approximately 8% of residual strain under the same loading environment. It can be seen that the steel connection experience smaller rotation capacity, smaller energy dissipation capacity, and higher residual strain curve compared with the smart connection, energy dissipation capacity is defined as the area inside the hysteresis loop.

The strain rate effect is studied intensively since blast wave pressure is high strain rate loading. Consequently, it is confirmed that at strain rate 458s\(^{-1}\) and 470s\(^{-1}\), the NiTi-SMA bolts can still provide flag-shaped hysteric loop behavior. Due to the deformation of some components of the connection, the enclosed area of the hysteresis loop is altered. Overall, the presented result confirmed that the proposed smart connection configuration actively utilizes the hysteresis behaviour of NiTi-SMA bolts.

6 Conclusion

In this study, at first, steel beam-column joint configuration is proposed based on Eurocode 3. Second, the simplified Kingery Airblast Calculations approach is employed to develop blast reflected over-pressure. The equivalent static blast loading is applied in the global 2D analysis. Third, the effect of NiTi-SMA bolts is included to study the effect of smart connection in the global 2D frame model. Based on the design verification in Ultimate Limit State, two different connection configurations are proposed. Finally, two sub-models are created in finite element software to study the energy dissipation, and recentring capacity of the NiTi-SMA-based smart connection numerically. Further analysis is conducted by replacing the NiTi-SMA bolts with steel bolts to exhibit the effect of smart connection.

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