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Enhancement of moment resistance of steel beams with initial imperfections and residual stresses by using stiffeners and GFRP plates

Phe Van Pham [a,b,*]

[a] Faculty of Civil Engineering, University of Transport and Communications, Hanoi, Vietnam.

[b] Research and Application center for technology in Civil Engineering (RACE), University of Transport and Communications, Vietnam.

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ABSTRACT

The present study proposes three strengthening solutions for wide flange steel beams having residual stresses and initial imperfections. In Solution 1, a midspan web stiffener is applied to such beams, aiming at reducing local web buckling. In Solution 2, two GFRP plates are bonded to the beam flanges in order to reduce local flange buckling. Solution 3 is a combination of the Solutions 1 and 2. Moment resistances of the strengthening systems are numerically evaluated and compared against those of the corresponding bare beam. Key observations obtained include (i) All Solutions 1, 2 and 3 are effective in increasing the moment resistance of the beam structure, (ii) When initial imperfection and residual stresses are excluded, the failure mode of the bare beams is mostly governed by local flange buckling. The moment resistances of the steel beam in Solution 1 are approximately equal to a fully plastic section moment. Meanwhile, the moment resistances of Solutions 2 and 3 are based on GFRP rupture failure mode. The strengthening solutions by using GFRP plates are the most effective while the addition of a web stiffener only plays a minor role, (iii) When initial imperfection and residual stresses are included, the failure mode of the steel beams is governed by local web buckling. The web stiffener in Solutions 1 and 3 plays an important role to increase the beam moment resistances. And (iv) For long spans, the moment resistances of Solutions 2 and 3 are significantly higher than those of Solution 1.

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1 Introduction and description of the problem

A simply supported steel beam subjected to a midspan point load P at the section mid-height (Fig. 1a) is considered. The beam is laterally unsupported and it has a prismatic $W250\times45$ cross-section (Fig. 1b). Steel is a perfectly plastic material

* *Corresponding author. Tel.: +84 0865651184.*
E-mail address: phe.phamvan@utc.edu.vn

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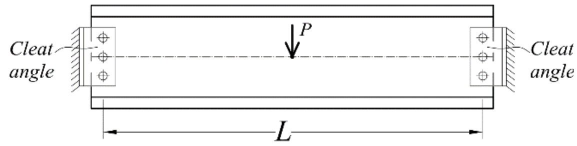
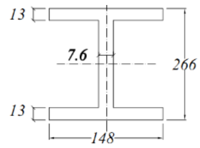
with an elastic modulus of $E = 200GPa$ and a yielding strength of $F_y = 350MPa$. Span lengths L=4.0 and 6.0m are considered.



(a) Beam profile

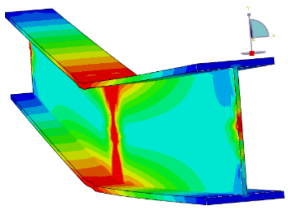


(b) W250x45 section

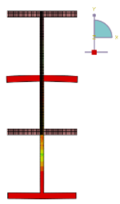
Fig. 1 – A simply supported beam subject to a midspan point load

There were many studies conducted for the given steel structures [e.g., 1,2], most studies however neglected the effects of imperfection and residual stresses initially stored in the beam. The present study develops a numerical study incorporating the effects into the steel beam. Details of the numerical study is going to be discussed in Secttion 2 of the present study. Based on such a numerical study, it is observed that deformations of the bare beam with and without the effects of residual stresses and initial imperfections are significantly different, as depicted in Fig. 2. In which, the bare beam excluding the effects is transversely deformed and its flanges were slightly locally buckled (Fig. 2b). Meanwhile, in the bare beam including the effects, the bare beam is transversely, laterally and twistedly deformed and its web was locally buckled (Fig. 2d). The difference of deformations between the two cases leads to the differences of moment resistances M_r as presented in Fig. 3, in which the bare beam excluding the effects (denoted as "*Mr-Bare beam-NoIM-NoR*") passed the design resistance curves evaluated from Canadian code (CSA-S16) [3] and Eurocodes 3 [4]. However, the moment resistances of the bare beams with the effects (denoted as "*Mr-Bare beam-With IM4mm-WithR*") are significantly smaller than those of the CSA-S16 and Eurocodes 3 standard. This indicates that the effects of initial imperfection and residual stresses on the moment resistance is significant. This urges that a strengthening solution for the bare beam is necessary.

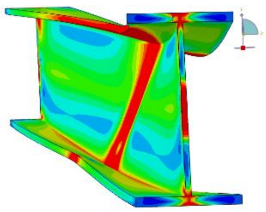
In order to reduce local web and flange bucklings, the present study proposes three strengthening solutions, those are named as Solution 1, Solution 2 and Solution 3. In Solution 1, a midspan web stiffener is applied to the steel beam, aiming at reducing local web buckling [5]. In Solution 2, two 9.5mm-thick GFRP plates are bonded to the top and bottom flanges by using 1-mm thick adhesive layers, aiming at reducing the local flange buckling [6,7,8,9]. Solution 3 is a combination of the Solutions 1 and 2 (Fig. 4). The GFRP plate has a longitudinal elasticity modulus of 17.2GPa and a rupture strength of 208.5MPa [6-9]. The adhesive material is Tyfo S with a modulus of 3.18 GPa and a tensile strength of 72.4 MPa. Moment resistances of the strengthening solutions are numerically evaluated and compared to those of the bare beam [10].



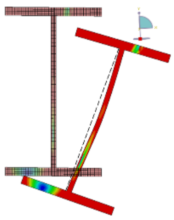
(a) Deformation of the bare beam without initial imperfection and residural stresses



(b) Undeformed and deformed midspan cross-sections of the beam in (a)



(c) Deformation of the bare beam with initial imperfection and residural stresses



(b) Undeformed and deformed midspan cross-sections of the beam in (c)

Fig. 2 – Deformation of the bare beams without/with initial imperfection and residual stresses

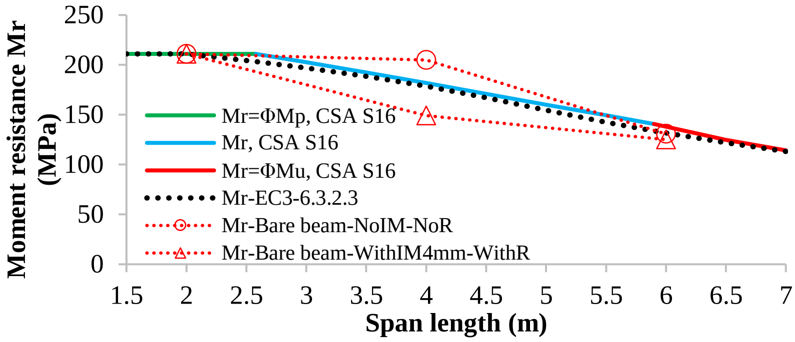


Fig. 3 – Moment resistances of the bare beams without/with initial imperfection and residual stresses, against those specified in CSA S16 code and Eurocodes 3

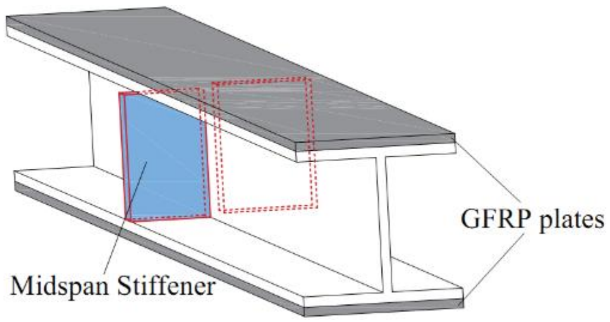


Fig. 4 – Strengthening beams by using a midspan web stiffeners and two GFRP plates

2 Modelling and failure modes

In the present study, a general numerical model (i.e., Solution 3) of W-steel beams with a mid-span web stiffener and bonded with two GFRP plates (Fig. 4) is conducted in ABAQUS [10]. By using Model Change keyword, a bare beam can be obtained by removing the elements of the stiffener, adhesive layers and GFRP plates from the general model. Also, the structure in Solution 1 can be obtained by removing the elements of adhesive layers and GFRP plates from the general model. Solution 2 can be obtained by removing the elements of the stiffener from the general model. The general model is based on brick elements C3D8R in the ABAQUS library. The element has 8 nodes with three translations per node, totaling 24 DOFs and adopts reduced integration to avoid volumetric locking, and thus has a single integration point located at the element centroid.

Implementation of initial imperfections: The present study assumes an initial imperfection based on their first lateral-torsional buckling mode shape with a peak magnitude of 4.0mm for all Solutions 1, 2 and 3 with spans L=4.0 and 6.0m (Fig.5). The value is equal to the allowable limit ([3,4]) for span L=4.0m (i.e., L/1000= 4000/1000= 4.0mm) and less than the allowable limit [3,4] for span L=6.0m (i.e., L/1000= 6000/1000= 6.0mm). The implementation is conducted by using keyword *imperfection.

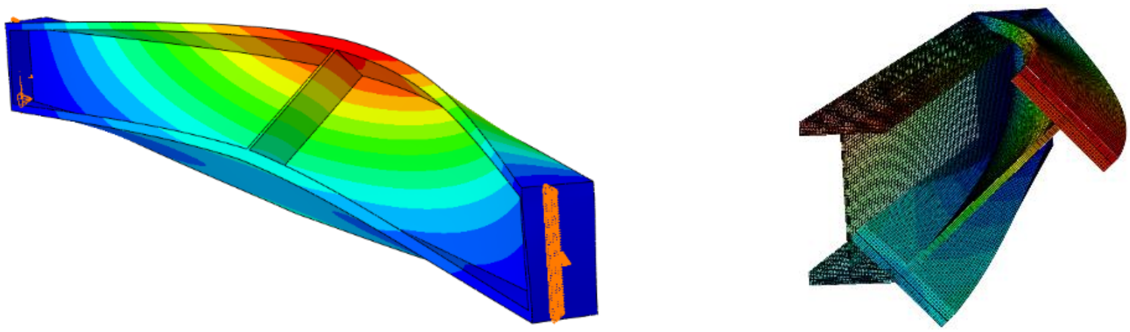
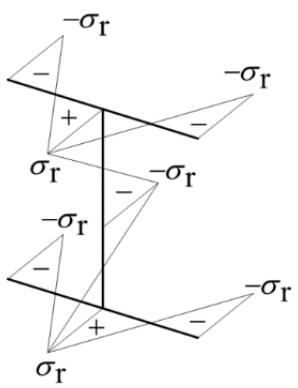


Fig. 5 – Implementation of initial imperfection into GFRP-strengthened beams through the first lateral-torsional buckling mode

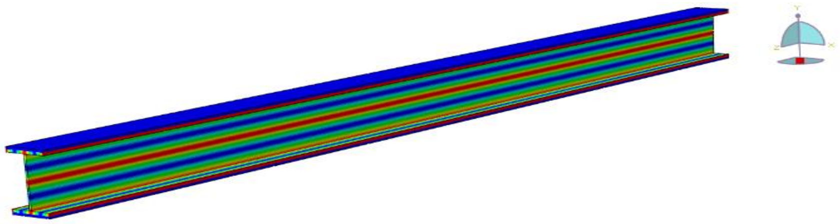
Implementation of residual stresses: Figure 6 presents a model of residual stresses distributed on steel cross-sections used in the present study, in which the value of σ_r is taken as $0.3F_y = 105MPa$. The residual stresses are incorporated into ABAQUS models through keyword *INITIAL CONDITIONS, TYPE=STRESS . A blank *STEP is then set to balance stresses in the steel, before the loading step is applied. By using this method, the stresses in the GFRP plate attached vanishes under the balancing of the residual stresses in the blank step (Fig. 6c) and no initial strain exists in the structure.

The FEA analyses are conducted to provides (1) elastic buckling moment resistances M_u through keyword *Buckle in *STEP level, and (2) inelastic moment resistances M_r through keyword *STATIC, RIKS in combining with a nonlinear geometric analysis by setting NLGEOM=YES. The number of increments, times step, the maximum and minimum iteration bounds are set as 50, 0.005, 1.0, 1e-008 respectively.

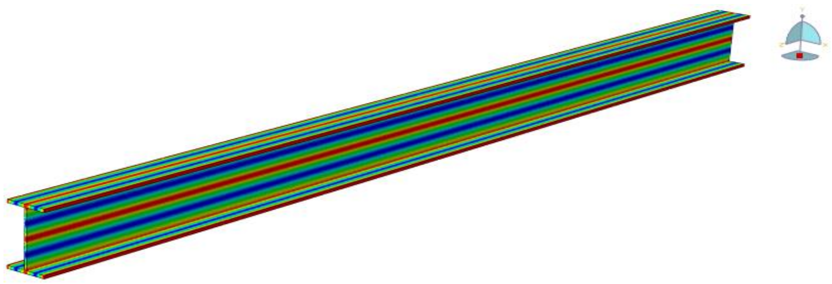
Failure mode: Moment resistance M_r of Solutions 1, 2 and 3 in the present FEA solution is based on the lower value of elastic buckling moment resistance M_u and inelastic moment resistance M_{in} . Besides, for the GFRP-strengthened beams in Solutions 2 and 3, the moment resistance also depends on adhesive/GFRP failure modes. The adhesive or GFRP is assumed as a failure mode if the peak tensile stresses in the layer exceeds its tensile strength. In the present study, only GFRP failure mode is observed.



(a) Residual stresses model



(b) Residual stresses in bare steel beams



(c) Residual stresses in GFRP-strengthned beams in the general model

Fig. 6 – Residual stress implemented into the ABAQUS models

3 Verification and result discussions

Figures 7a-d respectively present the inelastic moment resistance against midspan deflection of the bare beam and of the strengthening Solutions 1, 2 and 3 with span L=4.0m. The results, in which the effects of initial imperfection and residual stresses are excluded, are denoted as "*NoIM, NoR*". In contrast, the results with taking the effects are denoted as "*WithIM4mm, WihtR*". Also overlaid on the figures are the fully plastic section moment M_p and the elastic buckling moment M_u of the bare beam as evaluated from CSA S16 standard [3]. The elastic buckling moment M_u of the GFRP-strengthened beams in Solutions 2 and 3 are also presented in Figs. 7c-d. Table 1a,b summarize the elastic buckling moment resistances $M_u - FEA$, inelastic moment resistances $M_{in} - FEA$ and the moment resistances $M_r - FEA$ based on the present developed FEA model for the different Solutions with and without taking the effects of initial imperfections and residual stresses. For span L=4.0m, moments $M_u - FEA$ are higher than moments $M_{in} - FEA$, thus inelastic moment resistances governs the sytem failure, i.e.,the moment resistance of the system is $M_r = M_{in}$.

When the effects of initial imperfection and residual stresses are excluded (i.e., NoIM, NoR), the inelastic moment resistance and the moment resistances increases in the order of the Bare beam, Solution 1, Solution 2 and Solution 3 (Fig.7 and Table 1a). The moment resistance of bare beam and Solution 1 are nearly constant and approximately equal to the plastic section moments (Figs. 7a, b). In contrast, the moment resistances of Solutions 2 and 3 are based on GFRP failure mode at which the steel section has not been fully yielded. When compared to the moment resistance of the bare beam, the moment resistances of Solutions 1, 2 and 3 are 1.9, 25.9, and 28.2% higher, respectively (Table 1a). As depicted in Fig. 1a, the failure mode of the bare beam when the effects of initial imperfection and residual stresses excluded is mostly based on local flange buckling. Thus, the midspan web stiffener in Solution 1 may not be effective. In contrast, the beams strengthened with GFRP plates in Solutions 2 and 3 have the highest moment resistances (Table 1a) because they can reduce local flange buckling. This indicates that the strengthening solutions by using GFRP plates are the most effective while the web stiffener only plays a minor role.

When the effects of initial imperfection and residual stresses are included, a different picture is observed. By comparing Fig.7a against Fig. 7b or Fig. 7c against Fig. 7d, it is observed that the moment resistances of Solutions 1 and 3 (those have a midspan web stiffener) are significantly higher than those of the Bare beam and Solution 2 (those don't have a midspan web stiffener). The failure mode of the bare beam and Solution 2 is based on a local web buckling (as depicted in Fig. 1b). In contrast, the failure mode of Solutions 1 and 3 are not governed by the local web buckling. In particular, the failure mode of Solution 1 is close to a fully plastic section failure mode, while the failure mode of Solution 3 is based on a GFRP rupture failure mode. Therefore, the web stiffener in Solutions 1 and 3 are significantly effective in increasing the moment resistance of the strengthened system. In spite of that, it is also observed that all Solutions 1, 2 and 3 are more or less effective in increasing the moment resistance of the system (Table 1b).

When compared to the moment resistance of the bare beam, the moment resistances of Solutions 1, 2 and 3 are 36.7, 20.4, and 67.2% higher, respectively.

By comparing the moment resistances of Solutions 1 and 3 with/without the effects of initial imperfection and residual stresses (Table 1a,b) against the fully plastic section moment of the bare beam (i.e., 211 MPa), it is observed that the moment resistances of Solution 3 are significantly higher than, while those of Solution 1 are close to the plastic section moment. This indicates that the addition of GFRP plates significantly increase the moment capacity of the system far from the bare beam plastic moment. It is noted that the application of GFRP plates should be combined with the addition of a midspan web stiffener to reduce local web buckling as experienced in Solution 2 (Fig. 7c).

Figures 8a-d present the inelastic moment resistances against midspan deflection of the bare beam and of Solutions 1, 2 and 3 with span L=6.0m. The results excluding effects of initial imperfection and residual stresses are denoted as "NoIM, NoR", while those taking the effects are denoted as "WithIM4mm, WihtR". Also overlaid on the figures are the fully plastic moment M_p and the elastic buckling moment M_u of the bare beam section as determined in CSA S16 standard [3]. The elastic buckling moment M_u of the GFRP-strengthened beams in Solutions 2 and 3 are also presented in Figs. 8c-d. Table 1c,d provide the elastic buckling resistances $M_u - FEA$, inelastic moment resistances $M_{in} - FEA$ and the moment resistances $M_r - FEA$ based on the present developed FEA solutions with and without taking the effects of initial imperfections and residual stresses. The moment resistance $M_r - FEA$ of the system is based on the lower value of $M_u - FEA$ and $M_{in} - FEA$ When the effects of initial imperfection and residual stresses are excluded (i.e., NoIM, NoR), the failure mode of the bare beam and Solutions 1, 2 and 3 all are governed by global elastic buckling mode, in which the elastic buckling moment of Solutions 2 and 3 are 30.8% higher than those of the Bare beam and Solution 1.

When the effects of initial imperfection and residual stresses are included (i.e., withIM4mm, WithR), the failure mode of the bare beam and Solution 2 are based on inelastic moment resistances while that of Solutions 1 and 3 is governed by global elastic buckling mode. This again indicates an important role of the midspan web stiffener in order to postpone the occurance of local web buckling.

By comparing the moment resistances M_r of Solution 1 against those of Solution 2 and 3 (Table 1c,d), it is observed that the moment resistances of Solutions 2 and 3 are significantly higher than those of Solution 1. This implies that the Solutions 2 and 3 (two GFRP plates are applied) are more effective than Solution 1 (no GFRP is applied) for the long span.

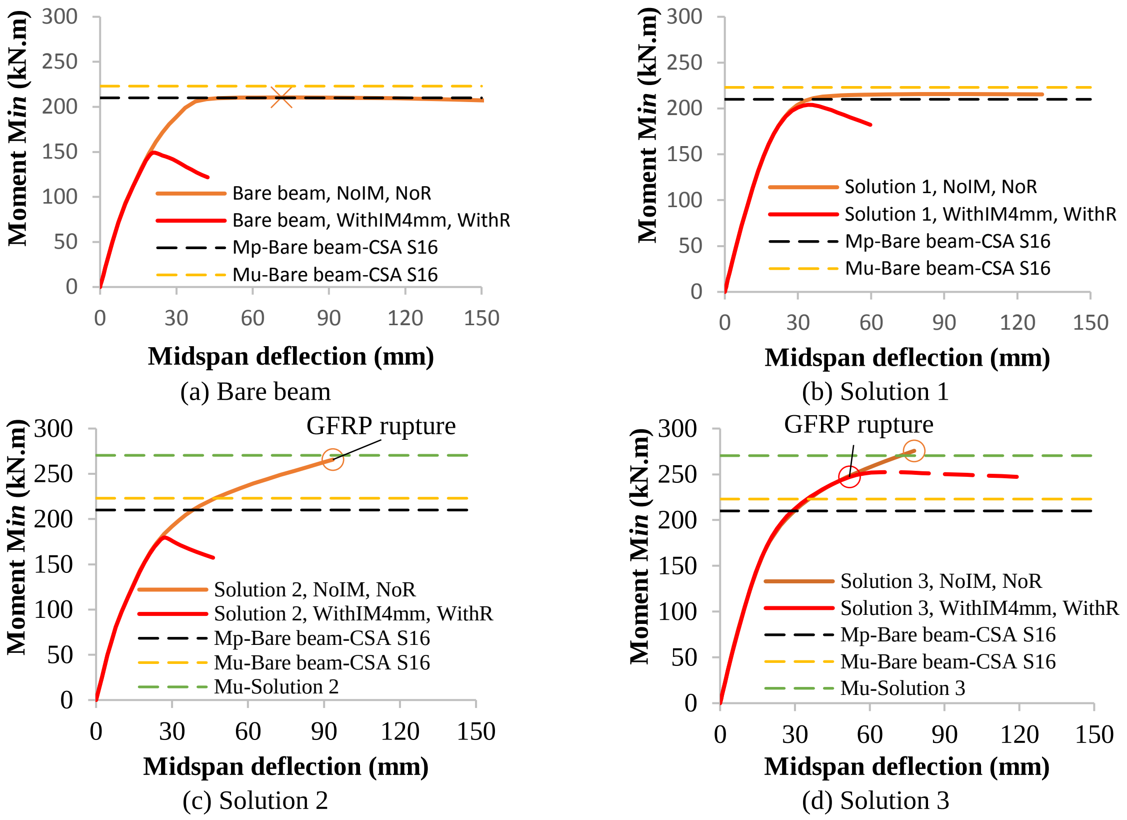


Fig. 7 – Inelastic moment resistance-midspan deflection relationships between different solutions for the beams with span L=4.0m

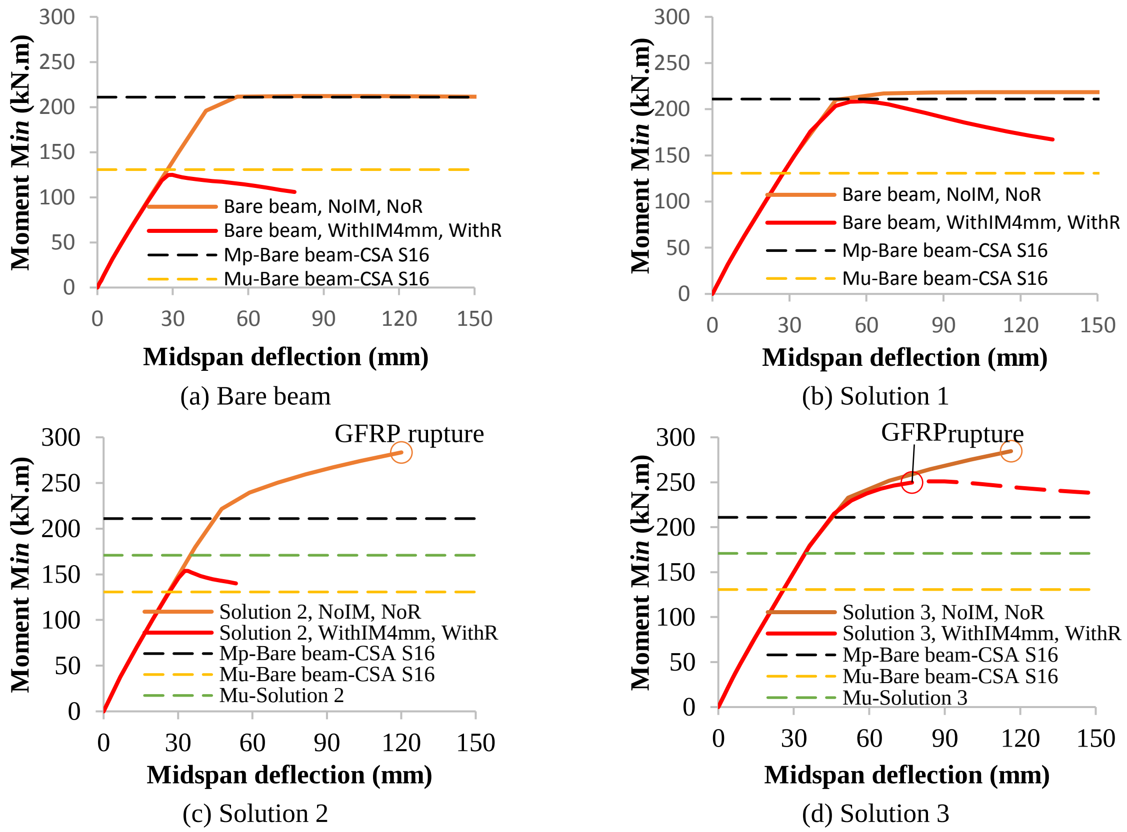


Fig. 8 – Inelastic moment resistance-midspan deflection relationships between different solutions for the beams with span L=6.0m

Figures 9, 10 and 11 present the comparison of moment resistances of the Bare beam and Solutions 1, 2 and 3 against the design values evaluated from CSA S16 [3] and Eurocodes [4] standards for spans L=4.0 and 6.0m. It is observed that moment resistances of Solutions 1, 2 and 3 passed the standard design moments. Solution 3 is the most effective in increasing the moment capacity of the system.

Table 1 – Comparisons of moment resistances between different solutions

Span (m)	Effect	Structures	M_u-FEA	M_{in}-FEA	M_r-FEA = min(M_u, M_{in})	% increase*
L=4.0	(a) NoIM, NoR	Bare beam	223.0	211.0	211.0	0.0
		Solution 1	223.0	215.0	215.0	1.9
		Solution 2	270.4	265.7	265.7	25.9
		Solution 3	270.4	275.2	270.4	28.2
	(b) WithIM4mm, WithR	Bare beam	223.0	149.2	149.2	0.0
		Solution 1	223.0	204.0	204.0	36.7
		Solution 2	270.4	179.6	179.6	20.4
		Solution 3	270.4	249.5	249.5	67.2
L=6.0	(c) NoIm, NoR	Bare beam	130.7	211.0	130.7	0.0
		Solution 1	130.7	215.0	130.7	0.0
		Solution 2	170.9	283.5	170.9	30.8
		Solution 3	170.9	284.6	170.9	30.8
	(d) WithIM4mm, WithR	Bare beam	130.7	125.0	125.0	0.0
		Solution 1	130.7	208.6	130.7	4.6
		Solution 2	170.9	153.8	153.8	23.0
		Solution 3	170.9	249.7	170.9	36.7

* % increase of a Solution i = (Mr of Solution i – Mr of the Bare beam)*100/ Mr of the Bare beam

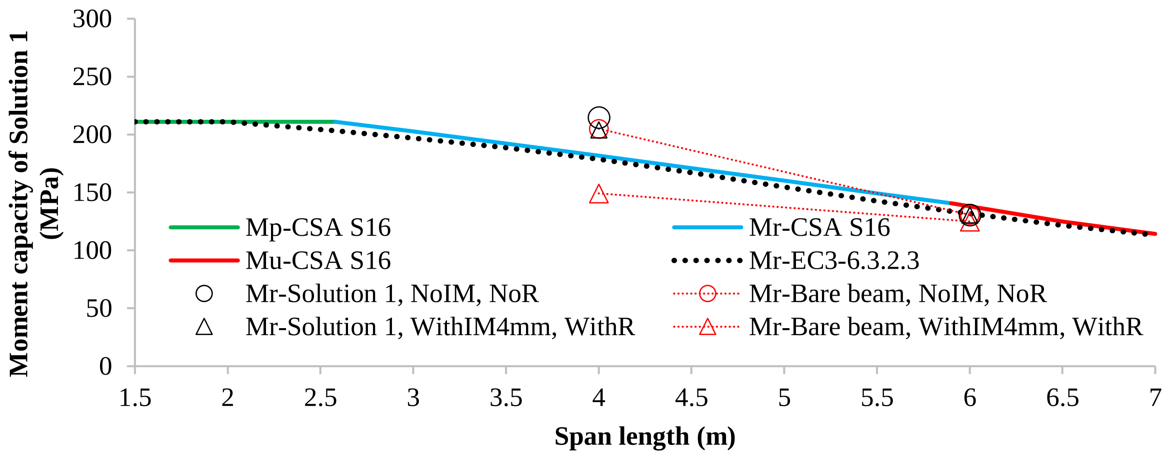


Fig. 9 – Comparison of moment capacities between Solution 1 and CSA-S16 and Eurocodes codes

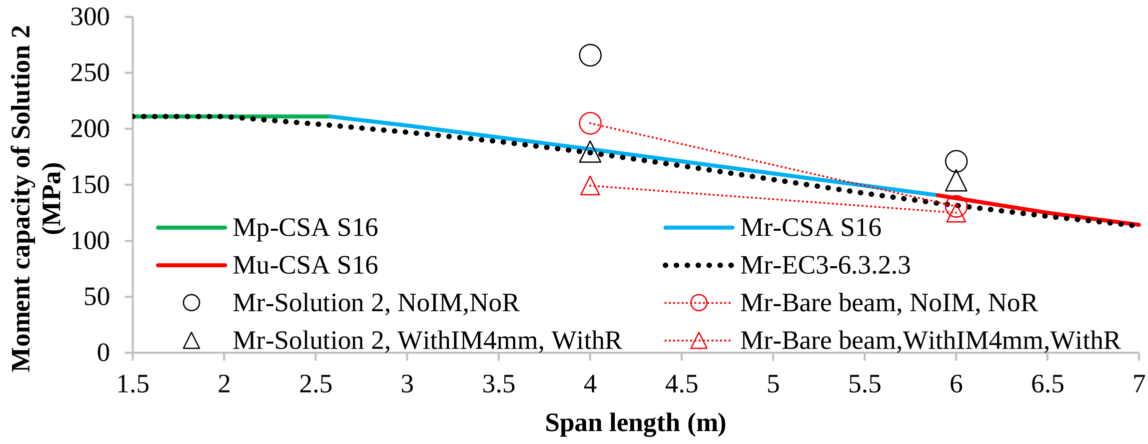


Fig. 10 – Comparison of moment capacities between Solution 2 and CSA-S16 and Eurocodes codes

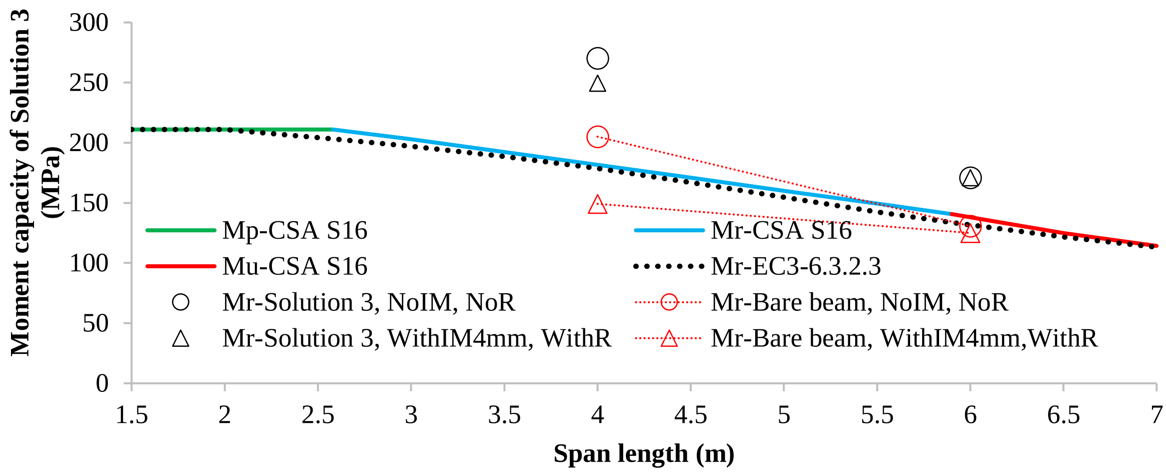


Fig. 11 – Comparison of moment capacities between Solution 3 and CSA-S16 and Eurocodes codes

4 Conclusions

The present study proposed three strengthening Solutions for wide flange steel beams with intermediate span lengths and with the effects of residual stresses and initial imperfections, in order to reduce local web and flange buckling. In Solution 1, only a midspan web stiffener was applied to the bare beam. In Solution 2, only two GFRP plates were bonded to flanges. And Solution 3 was a combination of Solutions 1 and 2. Moment resistances of the systems are numerically evaluated and compared to those of the bare beam. Key observations in the present study include: (***i***) All Solutions 1, 2 and 3 are more or less effective in increasing the moment resistance of the system. (***ii***) When the effects of initial imperfection and residual stresses are excluded, the failure mode of a bare beam is mostly based on local flange buckling. Moment resistances of the bare beam and Solution 1 are nearly constant and approximately equal to a fully plastic section moment. In contrast, the moment resistances of Solutions 2 and 3 are based on a GFRP rupture failure mode at which the steel section has not been fully yielded. Solutions 2 and 3 have the highest moment resistances because they can reduce the local flange buckling. The strengthening solutions by using GFRP plates are the most effective while the midspan web stiffener only play a minor role. (***iii***) However, when the effects of initial imperfection and residual stresses are included, the failure mode of the bare beam is mostly based on local web buckling. For both spans L=4.0 and 6.0m, it is observed that the moment resistances of Solutions 1 and 3 (those have a midspan web stiffener) are significantly higher than those of the Bare beam and Solution 2 (those don’t have the stiffener). The addition of the web stiffener in Solutions 1 and 3 is significantly effective in increasing the moment resistance of the strengthened beam. And (***iv***) For long span (e.g., L=6.0m), the moment resistances of Solutions 2 and 3 (with having GFRP plates) are significantly higher than those of Solution 1 (without having GFRP plates). In summary, a midspan web stiffener can ensure to maximize the moment resistances of the GFRP-strengthened beams as well as to minimize local web buckling.

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