Experimental investigation of parallel restrainers effects on buckling-restrained thin steel plate shear walls

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ABSTRACT

A novel, simple to apply, and economic buckling restrainer system is introduced for steel plate shear walls. The shear wall panel is restrained by parallel non-welded channel restrainers, which are installed on both sides of the steel panel. A set of experiments were designed to examine improvement in the seismic performance of the shear wall due to the application of the proposed restrainer system. Three 1/4-scale down single-story single-bay steel panel specimens including one panel without and two panels with different number of restrainers are subjected to cyclic loading. The behavior of steel panel with and without the restrainers is assessed in terms of initial stiffness, ultimate loading capacity, stiffness/strength degradation, and energy dissipation capacity. The use of the proposed restrainer system significantly improves the energy dissipation capacity of the shear wall and this enhancement is increasing at larger drifts. Employing the proposed restrainer system, there is only a slight increase in the ultimate loading capacity, and at the same time, a significant increase in the initial stiffness of the shear wall. No strength degradation is observed for the range of the drifts up to 5%. A design recommendation for the sizing of the parallel restrainer components is also included.

1. Introduction

In the recent engineering applications, steel plate shear walls (SPSWs) have been at the center of attention as the lateral force-resisting system around the world (Astaneh-Asl 2001; Sabelli and Bruneau 2007). They provide high initial elastic stiffness, excellent energy dissipation capacity, superior ductility, and stable hysteretic performance (Driver et al. 1998; Sabouri-Ghomi and Gholhakia 2008; Yu et al. 2018c; Chen et al. 2004). Considering the slenderness of these plates, they are susceptible to buckling at the early stage of loading. To improve the panel buckling resistance, it is feasible to increase the thickness of the steel panel; nevertheless, for moderate or strong earthquake buckling will be inevitable (Thorburn, Kulak, and Montgomery 1983; Lubell et al. 2000; Qu et al. 2008; Nie et al. 2013). After buckling, the shear force is carried out by diagonal tension-fields, exerting additional moment on horizontal and vertical boundary elements (VBEs) (Qu et al. 2008). Moreover, for the changing direction of loading, tension-field develops in different directions, which is accompanied with a snap-through that could endanger the stability of the structure. To increase the buckling resistance and improve the seismic performance of SPSWs, different concepts of buckling-restrained (BR) SPSWs and composite SPSWs have been devised by researchers (Yu et al. 2018a). Some particular methods are endeavored to prevent buckling of steel panels. Guo et al. (Guo, Dong, and Zhou 2009) studied the performance of SPSW buckling restrained by placing reinforced concrete panels on both sides of the steel plate. Because of the weak bonding between steel plates and concrete panels, the concrete panels are susceptible to separating from the steel plates. Another disadvantage of this buckling restrainer system is its heavyweight. Maurya and Eatherton (Maurya and Eatherton 2013) have proposed a new type of shear walls called ring-shaped SPSW (RS-SPSW). The ring-shape is the critical feature of the proposed system and its cutting pattern has a crucial impact on the system performance. In comparison with the free infill panel, the adoption of RS-SPSW results in higher energy dissipation and a more stable hysteretic response. The behavior of self-buckling-restrained (SBR) SPSW structure has been explored by Wang et al. (Wang, Xue, and Xiao 2017). The SBR-SPSW is made up of two inclined-slotted infill plates (ISIPs) which are bonded together by a rubber panel. The main concept is that under cyclic loading, when strips on one plate are in compression, concurrently the other inclined strips are in tension and provide out-of-plane support to those in compression. They conducted a sensitivity analysis to investigate the effect of strips and slots width through finite element method (FEM) analyses. The resulted SBR-SPSW has desired energy dissipation capacity and seismic performance (Wei et al. 2017a).

Considering the general efficiency of the SPSW structures, the deployment of stiffeners considerably
improves it through providing sufficient out-of-plane restraining for the infill steel plate (Chen and Guo 2012). In this context, Elgaaly et al. (Elgaaly 1998) and Sabouri et al. (Sabouri-Ghomi 2012) conducted investigations on SPSWs with and without stiffeners. The results indicated that local and overall buckling occurs at smaller drifts in the non-stiffened walls compared to stiffened one. Sigariyazd et al. (Sigariyazd, Joghataie, and Attari 2016) investigated the behavior of SPSWs with diagonal stiffeners in various configurations. They have shown that diagonal stiffened SPSWs have remarkable energy dissipation capacity.

Although there are considerable contributions from different researchers, there are still some techno-economic issues to be tackled. For example, in the case of precast concrete panels are weighty and employing of this type of restrainers leads to effects of infills on the peripheral frame (Wei et al. 2009). Another negative side-effect stems out from the fact that most stiffeners are connected to steel panels by welding, while the web of SPSW is considered to be a protected zone by AISC 341 (AISC, American Institute of Steel Construction (AISC) 2016a), this could trigger fracture of the web propagating into the boundary elements. On an attempt to annihilate some of these defects, Ge et al. (2017) proposed using non-welded multi-rib stiffeners attached on both sides of the steel panel as a substitute for prevalent stiffeners. These stiffeners are connected by blots through the steel plate and are not engaged in lateral load-carrying system. Installing the non-welded-multi-rib stiffeners has contributed to prevent the local buckling of the steel plate before yielding and it was simple to install on-site and reduces welding operations. Based on the same technique, Ge et al. (2017) and Yu et al. (2018a) have evaluated the dynamic performance of stiffened steel shear walls using FE modeling and compared the outcome with experimental results. In the meantime, Du et al. (2018) investigated the effect of multi-ribbed grid of channels’ stiffeners on the elastic stiffness and energy absorption. A one-span and two-story specimen that was damaged in the first stage was tested under cyclic load after installing the multi-ribbed gird stiffeners. The results indicate that the installation of a multi-ribbed grid of channels drastically reduces pinching. Using FE analyses, they found a significant increase in the yield load, initial stiffness, and ultimate load-carrying capacity. A new design of restrainers, shaped in the form of a cross, has been applied on shear walls by Yu et al. (Yu et al. 2018b). The purpose of this study was to interrogate the stress distribution on the panel surface and out-of-plane deformation phenomena. The results indicate that using this type of restrainers, there are improvements in load-carrying capacity, energy absorption capacity, and ductility.

Reviewing experiments on unstiffened SPSW reveals that the aspect ratio of the web plays a dominant role in configuring its seismic performance. Figure 1 depicts the correlation between SPSW aspect ratio and attainable displacement ductility and maximum inter-story drift obtained compiling results from different researches (AISC, American Institute of Steel Construction 2016b, GB/T 228.1 2010 2010, GB/T 2975–2018 2018, De Matteis et al. 2016, American Society for Testing and Materials 2006a, Wei et al. 2017b, Behbahaniord 2003). As could be seen, for the increasing aspect ratio of the SPSW, there are substantial increases in the displacement ductility and maximum inter-story drift. This pattern of behavior suggests that adopting a pattern of stiffeners that increases the aspect ratio of the web between the stiffeners and boundary elements could result in a large enhancement in the seismic response of the SPSW.

This paper proposes a new type of SPSW referred to as buckling-restrainedBR-SPSW considering both technical and economic issues. The BR-SPSW wall also exhibits better energy-absorbing characteristics even without requiring moment connections between boundary elements. In the devised approach, accounting for the importance of aspect ratio of web parts between stiffeners and boundary elements uses parallel-channel restrainers which are installed on both sides of the steel plate. Compared to a standard SPSW which has one variable controlling its seismic performance that is the web plate thickness, the proposed system, with a pattern intentionally spaced restrainers provides better control on the seismic performance of SPSW. Avoiding welding in the assemblage of the stiffeners, the proposed buckling restrainer system does not require welding to the web that could lead to its fracture under cyclic loading and at the time is easy to

Figure 1. Effect of aspect ratio on: (a) displacement ductility; (b) maximum inter-story drift.
apply. Three 1/4-scale down single-story single-bay steel panel specimens are considered with and without the proposed buckling restrainer system. These specimens are explored to evaluate their effect on the cyclic loading where the main interested metrics include initial stiffness, ultimate loading capacity, and failure mode. Moreover, stiffness degradation, energy dissipation capacity of the panel, and out-of-plane deformation of infill steel plates are the other parameters of interest. First, details of experimental program are introduced, and then reviewing the experimental results, the efficiency of the proposed buckling restrainer system is investigated.

2. Experimental program

2.1. Test setup

The experiments are carried out employing a universal jack of 1000 KN capacity in infrastructure research center of Urmia university. Figure 2 demonstrates the experimental setup developed at the laboratory. The left horizontal boundary element (HBE) is welded to the reaction truss that is connected by high-strength bolts to the strong floor. Lateral load is applied in the vertical direction by a 1000-KN hydraulic servo actuator with a stroke of ±300 mm. Lateral braces are located on either side of the loading column (Figure 2c). Measurements during tests, including out of plane deformation of the specimens, have shown adequacy of adopted measures. To reduce the influence of friction on the lateral braces of the loading column, they are connected to the column by frictionless wheels.

To measure the vertical displacement of the frame and accounting for limitation in stroke length, a Linear Variable Differential Transformer (LVDT) is installed in the middle of the lower VBE. Another LVDT is used to monitor possible horizontal displacement of reaction truss. The loading program is imported into the jack steering system as a displacement history. A Pancake load cell, at the bottom of the actuator, is used to record the load during the test process. All of the
measuring equipments are initialized to zero before the start of loading. During the test, displacements and forces are recorded with small steps to monitor and detect the hysteretic response.

The configuration and dimensions of the specimens are shown in Figure 3. To prevent local buckling and damage, the corners of the infill plate are chamfered as shown in Figure 3(b). To eliminate the contribution of the frame in the lateral force-resisting system, pin-joint is used in the connection between VBEs and HBEs. Figure 4 shows the hinged connection between VBE and HBE, where a single M30 grade 10.9 bolt is used.

The panel is bolted to angle sections that are welded to HBEs and VBEs. The angle dimension is 50 x 50 x 5 mm (depth by width by thickness) and for the connection of each side, 16M12 grade 8.8 bolts with center-to-center distances of 50 mm are used.

2.2. Specimens

This study includes three tests on specimens with and without the parallel restrainers. Specimens are 1/4-scale models that are designed according to the AISC 341–16 and AISC Design Guide 20 (AISC, American Institute of Steel Construction (AISC) 2016a, AISC, American Institute of Steel Construction (AISC) 2016b). Setup is designed in such a way that the frame and connections have enough stiffness and remain elastic before yielding of steel panel. The description and specification of the specimens are given in Table 1 and are depicted in Figure 5. Noting that the loading direction is vertical, restrainers are arranged parallel to the HBE to develop shear plane and benefit from enhanced shear deformation characteristics of a shear plane with high aspect ratio. As could be seen in Table 1, the use of restrainers has resulted in a large increase in the aspect ratio of the panel surrounded by the restrainer and boundary elements. The steel plates have been sampled and tested according to the assumptions and criteria addressed in (GB/T 228.1 2010 2010, GB/T 2975–2008 2018, De Matteis, Saracco, and Brando 2016). Figure 6 shows the stress-strain diagram of the panel plate and Table 2 gives material properties and dimensions of the panel, boundary elements, and restrainers.

2.3. Loading protocol

Loading protocol of SAC (ASTM, American Society for Testing and Materials 2006) as is depicted in Figure 7 is used as displacement history in this study. Based on previous studies (Wei et al. 2017b; Shekastehband, Azaraxsh, and Showkati 2018), the maximum lateral drift is set at 5%. FEMA 350 (FEMA-350 2000) for special moment-resisting frames (SMFs) suggests...
two drift angles corresponding to strength degradation and ultimate drift angles, which are 0.04 and 0.06, respectively. Considering these limitations on the required deformation capacity of SMF, it should be noted that the anticipated drift demand for SPSW systems is much smaller (about 0.02). Bearing in mind that testing using larger drifts can be hazardous to laboratory equipment and staff, it seems that 0.05 drift angle adopted in this study is adequate. As the steel frame is not a part of the lateral force-resisting system, no simultaneous gravity loading is applied.
Table 2. Summary of the material and dimensional properties of the specimens' components.

| Element     | Thickness (mm) | Width (mm) | Modulus of elasticity (GPa) | Yielding point stress (MPa) | Tensile strength (MPa) | Percent elongation % |
|-------------|----------------|------------|-----------------------------|-----------------------------|------------------------|-----------------------|
| Panel Coupon 1 | 0.70           | 19.82      | 200                         | 165                         | 288                    | 35                    |
| Panel Coupon 2 | 0.70           | 19.87      | 200                         | 167                         | 281                    | 35                    |
| Boundary     | IPE 200        |            | 210                         | 235                         | 340                    | 17                    |
| Restrainer*  | UNP 100        |            | 210                         | 235                         | 340                    | 17                    |

*ST37 material based on DIN 17,100 classification.

develops at the drift of about 1.5%. At the instance of plate buckling, for an increasing number of restrainers, there is a decrease in the intensity of the sound generated (also known as breathing effect), and for SP-3 R, this is completely averted.

- As shown in Figure 9, residual deformations are developed at the drift angle of 1.5% for specimens SP-WOR and SP-1 R, and at the drift angle of 2.0% in SP-3 R.
- As could be inferred from Figure 10, for an increasing number of restrainers, there is an increase in the number of buckling waves and inclination angle of the tension field.
- As depicted in Figure 11 and referring to Table 3, although the panel connections to the frames are done employing slip-critical connections with high-strength bolts, slides in some of the bolted connections near the panel corner have been occurring in SP-WOR and SP-3 R, while no slip is observed in SP-1 R joints.
- No tearing of the panel is observed at the end of the test at a lateral drift of 5%.

3. Observations and results

3.1. General observations

General observations regarding the performance of the specimens are given in Table 3 and are discussed in this section. Considering increasing displacements, these observations are

- Referring to Figure 8, initiation of buckling and formation of tension-field lines are concurrent in the specimens SP-WOR and SP-1 R, while for SP-3 R, buckling starts at the drift of 0.5% and tension-field

Table 3. Comparing performance of different specimens.

| Specimen | Start of initial buckling | Formation of the tension-field | Development of residual deformation | Slip between panel and connection angles (%) | Number of buckling waves | At drift of 4% |
|----------|---------------------------|--------------------------------|-----------------------------------|---------------------------------------------|-------------------------|---------------|
|          |                           |                                |                                   |                                             |                         | Tearing of panel plate at the end of test |
| SP-WOR   | 0.38                      | 0.38                           | 1.50                              | 3.00                                        | 7                       | 46° No        |
| SP-1 R   | 0.38                      | 0.38                           | 1.50                              | 5.00                                        | 8                       | 50° No        |
| SP-3 R   | 0.50                      | 1.50                           | 2.00                              | No                                          | 9                       | 59° No        |

3.2. Hysteric behavior of specimens

The hysteresis lateral load–displacement curves of the specimens are plotted in Figure 12 with the backbone

Figure 7. Time history of applied displacement.

the frame. Accounting for the specification of actuator, 20 mm/min loading speed is used.

Figure 8. Initial buckling waves: (a) SP-WOR; (b) SP-1 R; (c) SP-3 R.
Figure 9. Residual out of plane deformation: (a) SP-WOR; (b) SP-1 R; (c) SP-3 R.

Figure 10. Number of buckling waves in tension-field: (a) SP-WOR; (b) SP-1 R; (c) SP-3 R.

Figure 11. Slip in the corner of panel: (a) SP-WOR; (b) SP-3 R.

Figure 12. Hysteresis lateral load–displacement curves: (a) SP-WOR; (b) SP-1 R; (c) SP-3 R; (d) backbone.
curve represented in dashed-red line. All specimens show stable hysteresis behavior and no strength degradation or fracture is observed until the end of the test. Figure 12(d) compares the backbone of the specimens. It is evident that for increasing number of restrainers, the ultimate strength of all of the specimens is only slightly changed.

Observed pinching of hysteresis loops at different drift angles is consistent with those reported by other researchers (Wei et al. 2017b; Shekastehband, Azaraxsh, and Showkati 2018; Valizadeh, Shheidai, and Showkati 2012). To compare pinching extent in different specimens, Figure 13 depicts the first cycle to drift of 5% for all of the specimens. The following results could be captured according to this figure:

- From point a through to b, up to development of the tension-field, the slope of load–displacement curve is small. This behavior, which is visible in all of the specimens, is due to the cumulative plastic deformation of the web plate in the previous cycles and snap-through action. Applied force ratio to the ultimate strength of the specimen for SP-3 R is 0.19, while for SP-1 R and SP-WOR, it is 0.10 and 0.08, respectively.
- After point “b”, the stiffness of the element increases with the formation of the tension-field also known as post-buckling stiffness. By comparing the behavior of the specimens, the extent of horizontal plateau of the curve is shorter for SP-3 R and SP-1.
- After full development of tension filed at point c, there is a significant reduction in the stiffness of specimen. Also, it is evident that the specimen SP-3 R experiences more plastic deformation than the other ones.

Considering hysteresis response of the specimens, it could be concluded that SW-3 R experiences smaller pinching in its hysteresis response compared to SP-1 R and SP-WOR. This remark indicates effective performance of the parallel restrainers at closer intervals.

### 3.3. Strength and stiffness

Table 4 reports the elastic stiffness and ultimate strength of all of the specimens. Initial stiffness is evaluated considering slope of the specimen’s load–deflection diagram at small lateral drifts. Yield angle is also calculated as the point on the backbone where there is a substantial decrease in the slope of load–deflection diagram. Both parameters are also recalculated using the procedure proposed by Park (1989). By yielding of the web plate, the ultimate strength of all three specimens is approximately the same, with a slight increase for the increasing number of restrainers. The last two columns of the table reflect the normalized stiffness and shear strength of specimens against the corresponding values for SP-WOR. Considering the slope of load–deflection diagram at small drifts (Figure 14a), the initial stiffness values of SP-3 R and SP-1 R are 2.09 and 1.66 times of that for SP-WOR. This indicates a significant effect of restrainers on the initial stiffness of the shear panel. It can be seen that for larger drift angles, the impact of the restrainers on the hysteretic response is more pronounced. Figure 14(b) shows the hysteresis loops of the laboratory specimens at 1% drift angle, where the post-buckling stiffness of SP-3 R and SP-1 R is 79% and 56% higher than that for SP-WOR. Moreover, by evaluating the strength of the investigated specimens at different drift levels, it is seen that SP-3 R begins to yield at a drift of 1%, while in the SP-1 R and SP-WOR, panel yielding appears to occur at drifts of 1.5% and 2%, respectively.

### 4. Dissipated energy

Figure 15 compares normalized energy at different cycles to that in the first cycle at specific drift, which is an indicator of the stable energy dissipation of the specimen. This comparison is done for small and large drifts in Figure 15(a, b), respectively. As could be seen, in small drifts, there is no recognizable trend in the results, which could

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**Table 4. Summary of experimental results.**

| Specimen | Initial stiffness (kN/mm) | Yielding drift (%) | Yielding force (kN) | Ultimate strength, $P_{\text{max}}$ (kN) | Initial stiffness Rel. (kN/mm) | Ultimate strength Rel. (kN/mm) |
|----------|--------------------------|--------------------|--------------------|----------------------------------------|-------------------------------|-------------------------------|
| SP-WOR   | 1.07                     | 2.00               | 21.60              | 78.00                                  | 1.00                          | 1.00                          |
| SP-1 R   | 1.78                     | 1.50               | 35.20              | 79.00                                  | 1.66                          | 1.01                          |
| SP-3 R   | 2.24                     | 1.00               | 40.60              | 81.00                                  | 2.09                          | 1.04                          |
be aggravated by some errors in the measurements. In large drifts, superior response of SP-3 R is evident, where its energy dissipation in the subsequent drifts shows a more stable pattern compared to the other ones. The specimen SP-1 R lays between SP-WOR and SP-3 R, an indication of smooth transition to the better response for increasing number of restrainers.

Figure 16 depicts energy dissipation in the first cycle of the specific drift for increasing drift angles. As could be inferred, there is steady increase in the energy dissipation for larger drift that could be prime importance in limiting lateral deflection of the structure for intense ground motions. Comparing the performance of different specimens, energy dissipation of SP-3 R is more than 50% larger than the two other specimens, and there is little difference in this regard between SP-

Figure 16. Dissipated energy of the first cycle at specific drift for increasing drifts.

WOR and SP-1 R. This indicates that to have larger energy dissipation, smaller spacing between restrainers will be required.
4.1. Recommended design procedure for restrainers

In the design of restrainers, two approaches could be adopted. In the first approach, restrainers could be treated like HBEs and design requirements of AISC 341–16 for these elements could be used to size the restrainers (AISC, American Institute of Steel Construction (AISC) 2016a). In the second approach, these elements could be designed to adopt the design requirements of AISC 360–16 for stiffeners required for developing tension-field (AISC, American Institute of Steel Construction (AISC) 2016b). In the following subsection, these two approaches will be discussed in some detail.

4.2. Treating restrainer as HBE

AISC 341 has some stiffness and strength requirements for HBE, which are designed as capacity protected elements with some allowance for local yielding. The requirement could be listed as follows:

- **Local buckling requirement.** The allowance for local yielding resulted in the requirement that HBE should follow local buckling requirements for SMFs.
- **Design moment.** AISC 341 to avoid in-span plastic hinge in HBE requires that these elements should be designed for components of infill plate stress perpendicular to the HBE or reduced beam section should be provided at the connection with VBE to accommodate anticipated plastic rotation. Considering that the proposed restrainer does not have any connection to the plate in its length and its end connection in hinged, this requirement could be waived.
- **Connection of VBE to HBE.** This requirement mainly introduced to increase the stiffness of the lateral force-resisting system in the reloading stage, where significant pinching is anticipated. Using moment-resisting connection between beams and columns, it seems it will not be necessary to also have this type of connection between restrainers and VBEs.
- **Stiffness of HBE.** AISC 341 has some requirements for minimum stiffness of the HBE to guarantee full web panel yielding at smaller drifts. However as discussed in AISC 341, the better way will be to do a pushover analysis and size boundary element by its result. Considering that the restrainers end connections to the web panel are hinged, using pushover seems a more reasonable way to size the restrainers. To avoid this analytical method, a simple strip model could be used to evaluate force in the restrainers and also design its hinged connection to the web.

4.3. Treating restrainer as stiffeners

AISC 360 requirement for stiffeners to develop tension-field could also be used for proportioning the restrainers. In the following, we review requirements that could be used for this purpose

- **Stiffness requirement.** AISC 360–16 relationships can be used to design restrainers. The minimum inertia (Iₚ) of the stiffeners to fully develop the tension field could be calculated as

  \[
  I_p = \frac{a \cdot h^2}{12} + \frac{b_f \cdot h}{3}
  \]

  where \(a, h\) and \(t_w\) are clear distance between transverse elements, clear distance between the flanges and thickness of web plate, respectively, and \(b_f\) is smaller of dimension \(a\) and \(h\).

- **Connection spacing.** AISC 360 sets the maximum distance between the bolts connecting the stiffeners to 300 mm. In the case of specimens considered in this study, the distance between bolts is much larger than this limitation. As the results with much larger spacing is satisfying, smaller spacing of bolts is not used in this study. It could be anticipated that the system performance will be improved for smaller spacing of the connection bolts, although it will be accompanied with more workmanship.

5. Conclusion

A novel, easy to install, and economic arrangement of parallel restrainers is proposed in this paper. To study the efficiency of the system, three specimens of 1/4 scale with and without the proposed restrainers are subjected to cyclic loading of increasing magnitude. Results of tests could be summarised as

- Deploying parallel restrainers effectively controls the out-of-plane deformations and by increasing aspect ratio of the panels greatly improves the seismic performance of the SPSWs. Also, the possibility of breathing effect is greatly diminished by decreasing the spacing of the restrainers.
- There is no strength degradation even in drifts as large as 5%. Also, it is shown that the use of the proposed stiffeners results in even more stable energy dissipation in subsequent cyclic excursion. Some slippage was observed in the peripheral panel connections to boundary elements, which was eliminated for the case with smaller spacing between restrainers.
- There is increasing energy dissipation at larger drifts that could be further magnified employing stricter spacing of the stiffeners. This could be detrimental in limiting structural deformation in the case of very intense ground motions.
• Tension-field action starts at smaller drifts for panels with smaller spacing of the stiffeners and at the same time resisting force magnitude at reloading stage increase by as much as 2 times.
• The proposed system is easy to install and could be used for strengthening existing SPWSs suffering from strength deficiency or ductility.
• Based on AISC requirements, alternative design method is proposed that could be used for proportioning the restrainers.

Disclosure statement
No potential conflict of interest was reported by the authors.

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