Axial Compressive Characteristics of Brick Masonry Wall Strengthened by Steel Strips

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Abstract: In order to improve the compressive behavior of existing brick masonry walls, one of the most commonly used strengthening techniques is to use steel strips fixed on the masonry walls by the binding bolts, which has the advantages of easy construction and short construction period. Under axial compression, the criteria for judging the failure of strengthened masonry walls is that the masonry walls reach the peak strain or steel strips occur critical local buckling. Based on the stress-strain curves of the brick masonry wall and the steel, the axial compressive characteristics of brick masonry wall strengthened by steel strip is discussed, and a simplified formula to predict the load-carrying capacity of this type of strengthened walls is proposed and calibrated by collecting experimental results.

1. Introduction
Brick masonry is still used as a construction material in most of the countries, especially in the developing countries, because of its good heat insulation properties, high compressive strength, easy availability, good soundness, durability, and the low cost [1]. Furthermore, masonry structures cover a significant part of the existing buildings built before the 1980s in China and most of them need to be strengthened for improving their static load-carrying capacity or seismic performance. In recent years, strengthening of unreinforced masonry structures is getting more and more attention of civil engineers and researchers across the world [2-12], and the strengthening materials used include steel strips, steel reinforced composites, NSM FRP strips, ferrocement and GFRP, and so on. These methods have their own merits and have been applied in engineering practices.

Using steel strips fixed on the masonry walls by the binding bolts to improve the compressive behavior, such as load-carrying capacity and ductility, is increasingly favored by civil engineers. The schematic diagram of existing brick masonry wall strengthened by steel strips is shown in figure 1, in which the horizontal steel strips should be placed externally on the vertical steel strips to provide lateral support for them and to delay local buckling of the vertical steel strips. This method has the advantages of easy construction and short construction period. If necessary, the steel strips can be pre-stressed to increase their efficiency, i.e. to reduce the stress difference between vertical steel strips and brick masonry. Until now, some experimental investigations on the steel strips strengthening brick masonry under axial compression have been conducted [3]. However, to the best knowledge of the authors, no formulas are available in the literature to predict the load-carrying capacity of the existing masonry wall strengthened by steel strips (figure 1) under axial compression. In this paper, a simplified formula is proposed, which is based on stress-strain relationships of brick masonry and steel and the principle of strain compatibility.

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2. Stress-strain curves of brick masonry

Masonry structures are an assemblage of brick and mortar units which are described as orthotropic, inelastic and non-homogeneous. The mathematical modeling of stress-strain relationship for brick masonry is more complicated because of scarcity of controlled experimental tests and significant variation in material properties geographically [13].

Kaushik et al. proposed six control points on the stress-strain curve of masonry under axial compression [13], and Singh and Munjal proposed five control points to plot the compressive stress-strain curve of brick and concrete brick masonry [1]. Regardless of six control points or five control points, both of them adopt four points to plot the rising part of the stress-strain curve (see figure 2), i.e. 33%, 75%, 90%, and 100% of masonry strength ($f_m$). As for those four points, $0.33 f_m$ represents the point up to which the stress-strain curve remains linear. After this point, several cracks start developing in masonry and the stress-strain curve becomes nonlinear; $0.75 f_m$ indicates that vertical splitting cracks in bricks start occurring, but masonry still resists loads without much deterioration; $0.90 f_m$ means the stress level in masonry just before the failure when the vertical splitting cracks develop excessively throughout the masonry; $f_m$ is the peak stress in the masonry.

In the figure 2, the rising part of the stress-strain curve can be described by a parabolic curve [14-16], and the mathematical model is expressed in the equation (1).

$$\frac{f_m}{f_m} = 2 \frac{\epsilon_m}{\epsilon_m} - \left( \frac{\epsilon_m}{\epsilon_m} \right)^2$$

where $f_m$ and $\epsilon_m$ are compressive stress and strain in masonry, respectively; and $\epsilon_m$ is peak strain corresponding to $f_m$. $f_m$ and $\epsilon_m$ can be determined by directly tests or estimated by equations (2) and (3), in which $f_b$ and $f_{mo}$ are compressive stress of brick and mortar, respectively, both of them can be obtained in the design codes or by directly tests; $E_m$ is the elastic modulus of masonry and equals to 550 $f_m$ [13].
3. Stress-strain curves of steel strips

Steel strips are made of steel, and an ideal elastic-plastic relationship curve can be used for it, as shown in figure 3. However, during the loading process, the vertical steel strip used to strengthen the brick masonry walls would take place local buckling (see figure 4) when the ratio of spacing of lateral restraint to thickness of steel strips was too large. Corresponding to local buckling of the vertical steel strips, the critical buckling stress ($\sigma_{cr}$) maybe less than or greater than the yield strength ($f_y$) of the steel. In other words, the strength of steel may not be fully utilized due to its local buckling. Therefore, the contribution of vertical steel strips to the load-carrying capacity of the strengthened brick masonry walls depends on the smaller value of its yield strength and critical buckling stress. Assuming that the horizontal steel strips and binding bolts can provide effective lateral support for vertical steel strips, and the length of the half-wave where local buckling occurs between the lateral restraints ($s$), such as binding bolts or horizontal steel strips, is equal to 0.5 $s$. According to the Euler formula and considering the increase in unidirectional local buckling [3], the critical buckling strain can be expressed as the following equation, in which $t$ is the thickness of steel strips.

$$\varepsilon_{cr} = \frac{4\pi^2}{(s/t)^2}$$  \hspace{1cm} (4)
4. Failure criteria of strengthened masonry wall
Using steel strips to strengthen existing brick masonry walls, except for considering the maximum load-carrying capacity of the wall can resist, it is more important to consider the conditions allowed under usual service state. For example, in figure 4 the vertical steel strips took place local buckling is not allowed at service state.

As for masonry walls, when the compressive stress reaches $0.90 \ f_m$, the vertical splitting cracks develop excessively throughout the masonry. However, masonry wall’s carrying capacity can continue to increase and masonry wall is also confined by horizontal steel strips. Therefore, the criteria for judging the failure of strengthened masonry walls is that the masonry walls reach the peak strain or steel strips occur critical local buckling.

5. Proposed formula
Based on the above analyses, a simplified formula to predict the load-carrying capacity of brick masonry walls strengthened by steel strips is given in equation (5), in which $A_m$ is cross-sectional area of the masonry wall; $A_v$ is cross-sectional area of the vertical steel strips; $f_m$ and $f_y$ are compressive stress for masonry wall and vertical steel strip, respectively. $f_m$ is determined by equation (1) and $f_y$ is obtained by $E \varepsilon$ and not more than $f_y$. $\varepsilon$ is the compressive strain and determined by equation (6), in which $\varepsilon_{cr}$ is the strain corresponding to the critical stress of vertical steel strips and can be obtained by equation (4).

$$N = A_m f_m + A_v f_y$$

$$\varepsilon = \min (\varepsilon_m, \varepsilon_{cr})$$

It should be emphasized that the contribution of horizontal steel strips to the masonry wall in figure 1 is only limited to its lateral support for the vertical steel strips, i.e. the lateral confinement to the masonry wall is ignored because of the large ratio of width to thickness of masonry wall.

Based on the experimental results conducted by Farooq et al. [3], the tested loads ($N_T$) corresponding to the minimum value of peak strain of masonry wall and critical strain of local buckling of vertical steel strips can be reached, as shown in Table 1. The calculated loads ($N$) according to the above equations are listed in Table 1. From the Table 1, it shows that the proposed simplified formula has good precision.

Through the above analyses and calculation, it can be concluded that the spacing of the horizontal steel strips or the binding bolts has a great influence on the critical strain of local buckling of the vertical steel strips. In practical applications, in order to fully utilize the strength of the vertical steel strips, the spacing of lateral restraint to the vertical steel strips should be determined to assure the critical strain of local buckling to be equal to or close to the peak strain of masonry wall.

| Specimen | $A_m$ (mm$^2$) | $A_v$ (mm$^2$) | $f_m$ (MPa) | $f_y$ (MPa) | $\varepsilon_m$ | $\varepsilon_{cr}$ | $N_T$ (kN) | $N$ (kN) | $N / N_T$ |
|----------|----------------|----------------|-------------|-------------|----------------|----------------|-----------|---------|-----------|
| UM       | 139355         | /              | 4.5         | /           | 0.0047         | /              | 650       | 627     | 0.96      |
| FSM      | 139355         | 293            | 4.5         | 227.5       | 0.0047         | 0.004427       | 736       | 692     | 0.94      |
| SCM      | 139355         | 293            | 4.5         | 227.5       | 0.0047         | 0.001686       | 450       | 436     | 0.97      |
| DCM      | 139355         | 585            | 4.5         | 227.5       | 0.0047         | 0.001686       | 530       | 502     | 0.95      |

6. Conclusions
Using steel strips to strengthen existing masonry walls is one of the most commonly used strengthening techniques, and it has the advantages of short construction period and easy construction.
Under axial compression, the criteria for judging the failure of strengthened masonry walls is that the masonry walls reach the peak strain or steel strips occur critical local buckling. Based on the stress-strain curves of the brick masonry wall and the steel and the principle of strain compatibility, a simplified formula to predict the load-carrying capacity of this type of strengthened walls is proposed, which has a good agreement with tested results and can guide the design of practical projects.

Acknowledgments
This work was supported by the Natural Science Foundation of Jiangsu Province, China (Grant No. BK20171361) and the National Science Foundation of China (NSFC) (Grant No. 51008070).

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