A New Rule-Based Strategy to Determine The Failure modes of Structural Walls

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ABSTRACT

Parameters affecting types of failure of reinforced concrete structural walls with arbitrary aspect ratios and cross section are investigated using data from numerous wall tests. Basically there are three known primary failure modes that covers prominent behavior of wall at the failure load. Shear failure is known by diagonal tension cracks and premature yielding of shear reinforcement that leads to abrupt none-ductile failure. To insure a ductile flexural failure, it is recommended that strength in shear be equal or greater than strength in flexure. Flexural-shear failure is another type of failure that needs to more details to identify explicitly and it is divided to two different cases namely web crushing or sliding shear failure. A new model is proposed to predict the failure modes of structural walls in terms of shear strength, nominal shear stress, shear force related to flexural capacity, the level of compression in concrete and control of sliding shear failure.

Key words : failure modes of structural walls, shear failure, flexural failure, Sliding shear failure

1. Introduction

Failure modes of structural walls is one of the challenging objects facing structural engineers in recent decades. Basically recognition of the failure type of the structural walls, prepare useful information about the behavior of the wall under cyclic loading which is essential in damage assessment of structures. Moreover, energy-based damage indices, which uses energy absorption to developing the model, to give reasonable damage index, requires more accurate prediction of hysteric behavior of the wall. To achieving this goal, distinguishing between failure modes of the wall is unavoidable. Because, several experimental results, have shown that the failure mode, influences the type and rate of deterioration in the hysteric loops.

There are several Parameters affecting type of failure of the walls which has been focused by researchers. In this paper, after concise explanation of failure types and reviewing experimental-based models which attempted to identify the boundaries for all type of failures, important parameters that influence type of failure is identified and by using these parameters, some boundaries is proposed to separate all types of the failure modes of the structural walls.

2. Failure Types

There are three known types of failure for structural walls, namely flexural, flexural-shear and shear failures, each of which has particular characteristics that indicate the behavior of the wall at the failure load. Flexural failure is usually followed by buckling and yielding of vertical reinforcement with the crushing of cover of concrete.
Flexural- shear failure is divided into two different categories, namely web crushing and sliding shear failure. In web crushing mode, the wall fails soon after the yielding of flexural bars by forming a significant inclined crack and web concrete crushing (Figure 2). Sliding shear failure is another case which can only delay the crush of web concrete to a certain extent (Figure 3).

Shear failure is mode of failure which is known with diagonal tension cracks or immature yielding of shear reinforcement (Figure 4). In order to exactly model the hysteretic behavior of the walls and effectively decrease inaccuracies, the modes of failure should be differentiated.

3. Reviewing Experimental-Based Models to Distinguishing Types of Failure

Based on experimental results, a parameter study was done by Fang [3]. He concluded that, shear span ratio ($M/\nu L_w$), the ratio of shear strength to flexural capacity, nominal shear stress influence type of...
failure of the tall structural walls. Figure 5 and Figure 6 show these parameters and their effects on type of failure. In this figures, $V_u$ is the measured shear force during test, $V_s$ and $V_f$ are the shear force associated with calculated shear and flexural strengths respectively. $V_u / V_f$ is shear span ratio at wall bottom and $\frac{\tau}{\sqrt{f'_c}}$ is the nominal shear stress divided by the root of compressive strength of concrete.

Three patterns can be obtained from figures. First, structural walls with flexural predominate behavior have lower nominal shear stress ($\frac{V_s}{V_f} < 0.4$). Also structural walls that behave in flexural-shear manner have $\frac{V_s}{V_f} > 1$, but higher nominal shear stress ($\frac{V_s}{V_f} < 0.4$). Moreover, walls with shear failure, generally have $\frac{V_s}{V_f} > 1$ and this type of failure even is evidence for walls with high shear-to-span ratio.

Han et al [4] by theoretically investigation of some structural walls with various ratio of transverse and longitudinal reinforcement concluded that, when wall has small amount of steel in both direction, the failure is ductile and it is termed under reinforced plastic mode. If the wall has a large amount of steel, the failure is brittle. This fail is called over-reinforced mode. There is a failure mode between these two modes that is called under-reinforced mode, which is characterized by yielding of reinforcement in only one direction. He determined the boundary of the three failure modes in term of reinforcement ratios (Figure 7).
Figure 7. Boundaries of the three types of failure modes (Han, 1986)

In recent decade Most of the researches on the failure modes of the structural walls has been performed in term of analytical and theoretical investigations and experimental researches has been decreased significantly. Between experimental investigations, Yoshikava and Miyagi [5] defined parameter $\alpha_v$ to distinguish the failure modes of reinforced columns. $\alpha_v$ is the ratio of shear capacity obtained from experiments to shear force associated with nominal flexural capacity as follow:

$$\alpha_v = \frac{V_s}{V_f}$$  \hspace{1cm} (1)

Table 1. illustrates boundaries proposed by Yoshikawa et al to separate the failure modes of reinforced concrete columns.

| $\alpha_v$ | Flexural failure | Shear failure after yield of vertical reinforcement | Shear failure |
|------------|------------------|------------------------------------------------|--------------|
| $\geq 1.5$ |                  |                                                              |              |
| $0.8 \leq \alpha_v < 1.5$ |      |                                                              |              |
| $\alpha_v < 0.8$ |      |                                                              |              |

Grifenhagen based on experimental results, by using the same method of Yoshikawa and Miagi and implement some modification, investigated the failure modes of squat structural walls[6]. He focused on the shear behavior of walls and divided behavior of squat structural walls as elastic shear, low to moderate ductile and brittle behavior. Expression (2) was defined to clarify three probable behaviors.

$$\tau_m = \frac{\varphi M_n}{h_w l_w b_w} \quad \alpha_v = \frac{1.1 V_N}{V_R}$$  \hspace{1cm} (2)

Where, $M_n$ is nominal flexural moment at yielding, $\varphi$ is the overstrength factor, $h_w$ is the wall height, $l_w$ is wall length, $b_w$ is thickness of the wall, $V_N$ is shear capacity and $V_R$ is maximum expected base shear.
**Figure 8.** Failure modes and expected response of low-rise shear walls (Grifenhagen, 2006)

### 4. Proposed Model for Predicting the failure mode of structural walls

As it mentioned in previous section, there are several parameters which are affect the failure modes of structural walls. These parameters need many details to identify and this method actually are not applicable. Then, proposed approach is based on forces and stresses which some researchers focused on this method. for example, the amount of maximum shear force which wall can experience is influenced by shear- to- span ratio(H/L), the amount of reinforcements, confining and axial force.

\[ V_{\text{max}} = f(\rho_t, \rho_v, P, \frac{H}{L}, ...) \]  

(3)

Based on experimental observations ,There are three known failures. On the other hand, low ductility means shear failure and high ductility equivalent to flexural failure. In fact, by identifying the failure mode of the wall, the overall behavior of wall under cyclic loading and the state of damage will be more intelligible which is important in damage assessment. Figure 9 shows various types of failure of the RC walls and Figure 10 illustrates relationship between ductility and expected damage.

**Figure 9.** Various types of failure and expected damages of RC walls
5. Identified factors which are affective in the failure mode

5.1. Ratio of shear strength to shear force associated to flexural capacity
According to experimental results, it is obvious that shear strength of the wall be lower than shear force associated with flexural capacity, the failure occurs in shear mode. In this paper for calculating the flexural capacity of walls, ACI-318-08 code[7] was used. Also, based on experimental results[8], [9] computing the shear strength of RC walls with H/L < 1 is underestimated with using Codes and in some cases the error is significant. So in this paper, the shear strength of squat walls was calculated with experimental expression which was proposed by Hirosawa [10] as follows:

\[
V_y = \left\{ \frac{0.08\rho_t^{0.23}(f'_c + 2.56)}{\sqrt{\frac{M}{V_LW} + 0.12}} \right\} + 0.32\sqrt{f_y\rho_w} + 0.1f_d + b_eL_w
\]

Where, \(V_y\) is shear strength, \(\frac{M}{V_LW}\) is shear span ratio, \(\rho_t\) is amount of tension reinforcement, \(\rho_w\) is percentage of flexural reinforcement in web of the wall, \(f_d\) is shear stress, \(b_e\) thickness of the wall and \(L_w\) is distance between two boundary elements and expression is presented in Kips-inch unit.

5.2. Nominal shear stress
Experimental researches[3] has been shown that, the nominal shear stress of the wall can be good criteria for distinguishing the failure modes of structural walls. Generally walls with low shear stress have flexural dominate behavior.

5.3. Diagonal compression in concrete of the web
It is obvious that if the shear force which is applied to the wall, exceeds from specific amount, the concrete of the web causes the failure and increasing the reinforcement can not prevent this mode of failure.

5.4. Sliding-shear strength of the wall
Based on experimental investigations[8], [9] in some cases has been shown that sliding shear mechanism has been decreased ductility of the wall and lead to failure of the wall with severe pinching phenomenon. So, in this case, specially for squat structural walls identifying when this mechanism occur and in what ways results in sliding shear failure is important. Basically there are some well known factors that affect sliding shear strength. Dowel action strength of vertical reinforcement, concrete of compression zone and shear strength of diagonal bars if exist, are effective in sliding mechanism. Mattock investigated shear mechanism of concrete joints and conclude that, the monotonic shear strength at cyclic loading has been estimated as 20%[11]. Therefore, the shear capacity of the concrete compression zone was conservatively suggested to 0.25fi'. The contribution of the compression zone to the sliding shear strength then was limited to :
Where \( V_f \) is the contribution of concrete compression zone, \( f'_c \) is compressive strength of concrete, \( b_w \) is the width of concrete compression zone and \( x \) is distance from compression edge to neutral axis.

Also by considering the dowel action of vertical bars where, the yield strength of the vertical bars is reduced to 25% for that. Then, the shear strength against sliding shear failure can be presented by equation 6 [6]:

\[
V_t = 0.25b_w\left(\rho_v f_y l_w + f'_c x\right)
\]

Where, \( V_t \) is the sliding shear strength, \( l_w \) is the length of the wall, \( \rho_v \) is the ratio of vertical reinforcement in the web and boundary elements together and the rest of parameters were identified previously.

ACI recommended that 0.65\( \sqrt{f'_c} \) Mpa may be a suitable limit for shear stress beyond which sliding shear may become dominate. Despite ACI code which controls sliding shear failure by the level of shear stress acting on the section, European code suggested a explicit expression for sliding shear strength that include effective parameters in sliding shear strength[12]:

\[
V_{sd}=A_{sl}(f_{yd}\cos\phi + A_{sj}\min(0.25 f_{yd}, 1.3\sqrt{f_{cd}f_{yd}})) + \min(0.3(1 - f_{ck}(MP)/250)b_{w0}xf_{cd}, \\
\mu_f[A_{sj}f_{yd} N_{ED}x + \frac{N_{Ed}}{l}])
\]

Where \( V_{sd} \) is sliding shear strength, \( A_{sl} \) is total area of diagonal bars in two direction, \( A_{sj} \) is the area of vertical bars in the web and boundary elements together, \( b_{w0} \) is thickness of the wall, \( f_{ck} \) is the confined concrete compression strength, \( \mu_f \) is the friction coefficient of the concrete, \( N_{Ed} \) is the axial force which is positive when it is compressive, \( M_{Ed} \) is resistant moment of the wall and \( l \) is the moment arm.

In this paper, on the basis of mentioned researches equation (8) was recognized to computing sliding shear strength[13]:

\[
V_s=0.25b_w\rho_v f_y l_w + 0.3b_w f'_c x + A_{sl}f_{yd}\cos\phi
\]

The important point is that, if sliding shear strength be less than experimented shear force due to loading, it dose not mean, failure definitely occur in this mode( except walls with very less ratio of shear –to–span ration( H/L<0.25)). First, other types of failure should be controlled. Because may be before activation of sliding mechanism, the wall fails in web crushing or diagonal tension or in flexural ways.

6. Proposed model
In this study using numerous existing experimental results(about 105 specimen), According to identified parameters which mentioned above, new model is presented to distinguishing types of failure of RC structural walls with detail of the damage. Thus, nominal shear strength(\( V_s \)), shear force associated to nominal flexural capacity(\( V_f \)), nominal shear stress(\( \tau/\sqrt{f'_c} \)) and ratio of experimented maximum force due to loading to concrete shear strength (\( V_u/V_{cd} \)) was computed. Also if necessary, in some cases sliding shear strength(\( V_{slide} \)) was calculated. The data can be divided in two categories. Some results was used to developing the model and rest of them was used to verifying the model. Figure 11 shows details of proposed model[14].
Figure 11. details of proposed model

Also, walls with so low aspect ratio (H/L<0.25) are susceptible to sliding shear failure. So, in this cases, at first sliding shear failure should be controlled.

Table 2. shows the properties of selected specimens which, will be discussed in detail. Also Table 3. shows the calculations which compares results of the new model with experimental results.

Table 2. properties of the pattern specimens

| ref | specimen | shape | $\rho_f$ (% | $\rho_h$ (%) | $\rho_n$ (%) | $f'_c$ (MPA) | $f_y$ (MPA) | $h$ (mm) | $f_t$ (

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| [15] | R1 | | 1.47 | 0.31 | 0.25 | 44.75 | 450 | 4580 | - |
| [15] | B1 | | 1.11 | 0.31 | 0.29 | 53 | 450 | 4580 | - |
| [15] | B2 | | 3.67 | 0.63 | 0.29 | 536 | 450 | 4580 | - |
| [16] | B8 | | 3.67 | 1.38 | 0.29 | 42 | 447 | 4580 | 9.3 |
| [9] | Wall3 | | 1.8 | 1.6 | 0.36 | 26 | 380 | 1500 | - |
| [6] | M2 | | - | - | 0.3 | 51 | 504 | 690 | 1.7-2.9 |

In Table 2 $\rho_f$, $\rho_h$, $\rho_n$ are the percentage of main flexural reinforcement at boundary elements, the percentage of horizontal shear reinforcement and the percentage of vertical reinforcement at the
wall web respectively. \( f'_c \) is compressive strength of concrete, \( f_y \) is yield strength of flexural bars, \( P \) is axial force and \( A \) is the area of the horizontal section of the wall.

### Table 3. Calculation of Proposed Damage Index

| ref | specimen | vs(kN) | vf(kN) | vu(kN) | vs/vf | \( \tau/\sigma' \) (MPA) | Vc(kN) | Vu/Vc | Vs/\( \nu' \) | Vslide (kn) | status(model) | status(expe) |
|-----|----------|--------|--------|--------|-------|-----------------|--------|-------|-------------|-------------|---------------|--------------|
| [15] | R1       | 410    | 80     | 118.3  | 5.125 | 0.116256        | -      | -     | -           | -           | F             | F            |
| [15] | B1       | 415    | 202.6  | 271.3  | 2.048371 | 0.240625037     | -      | -     | -           | -           | F             | F            |
| [15] | B2       | 673.4  | 511.5  | 679.6  | 1.31652 | 0.59926341      | 17.88  | 3.800895 | -           | -           | F-S-1         | F-S-1        |
| [16] | B8       | 1341.8 | 767.8  | 977.7  | 1.747591 | 0.97443115      | 15.83  | 6.176248 | -           | -           | F-S-1         | F-S-1        |
| [9]  | WALL3    | 1156.7 | 673.6  | 790    | 1.717191 | 0.653           | 29.9   | 2.64214 | 317.4       | 17.88       | F-S-2         | F-S-2        |
| [6]  | M2       | 122.3  | 161.3  | 200    | 0.758215 | 0.35            | -      | -     | -           | -           | S             | S            |

In this table, \( V_s \) shear strength, \( V_f \) is shear force associated to yield strength, \( V_u \) is maximum experimented force due to loading, \( \tau \) is nominal shear stress, \( f'_c \) is compression strength of concrete, and \( V_{slide} \) is sliding shear strength. Flexural failure, flexural-shear failure(web crushing), flexural-shear failure(sliding failure)and shear failure was indicated by letters F, F-S-1, F-S-2 and S respectively.

### 7. Discussion

As can be seen in Table 1, for sample R1, the ratio of \( V_s/V_f \) is equal to 5.125. So the wall,dose not fail in shear. Then the nominal shear stress indicator \( \sqrt{\tau/\sigma'} \) was calculated .This ratio was less than 0.4 which means the failure will be flexural. Similar calculation for sample B1 indicates that this specimen also fails in flexural manner( \( V_s/V_f \) >0.9 , \( \sqrt{\tau/\sigma'} < 0.4 \)).

Specimen B2 because of significant increase of flexural reinforcement, experienced high level of shear force and has a ratio of \( V_s/V_f \) >1. Also it has a nominal shear stress about 0.6 which is greater than 0.4. So the failure is not flexural. In this case the level of compression in the web concrete should be considered. This specimen has a ratio of \( V_s/V_c \) was about 3.8 which was higher than identified boundary. This means that the level of compression in web concrete exceeded from specific boundary(\( V_s/V_c =3 \)) . As a result the wall fail in web crushing mode (F-S-1). In specimen B8, presence of high normalized axial force ( \( P/A_f f'_c = 9.3\% \) ) intensifies the level of compression in web concrete which increased the possibility of flexural-shear failure. Also for specimen wall3, after preliminary calculation, it was concluded, the computation the sliding shear strength of the wall is needed. As it can be seen in Table1 the estimation of sliding shear strength (317KN) was less than maximum shear experienced due to loading. Then, the failure of wall was sliding shear failure mode(F-S-2). Specimen M2 also is one of the evidence of shear failure because of lack of shear reinforcement. In this case, the ratio of \( V_s/V_f \approx 0.76 \) which was less than 0.9. Therefore this specimen failed in the shear manner.

### 8. Conclusions

In this paper, a new rule-based strategy was presented to separate the possible failure modes of structural walls which gives a useful information for damage assessment. Previous models, were not comprehensive for walls with arbitrary aspect ratios. Presented model is able to distinguish type of failure with detail of damage just before failure.
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