IMPROVING DUCTILITY AND SHEAR CAPACITY OF REINFORCED CONCRETE COLUMNS WITH THE RETRO-BELT™ RETROFITTING SYSTEM

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ABSTRACT

This paper presents an overview of the research done and the design principles and procedures developed for retrofitting existing reinforced concrete columns using a new seismic retrofit technique. This technique, the Retro-Belt™ retrofitting system, consists of prestressing strands and specially designed anchors placed and stressed externally on the column as individual hoops. The external pre-stressing forces, from the prestressing strands, provide hoop stress to the concrete, improving the confinement of concrete and hence ductility of column, while also improving its shear resistance. The level of pre-stressing, hoop spacing and strand size form the parameters of design, and can be selected to suit the size and retrofit needs of the column.

Studies conducted at the University of Ottawa have demonstrated that the Retro-Belt™ retrofitting system can effectively suppress shear and lap-splice bond failures, increase confinement, promote flexural behaviour, and substantially enhance inelastic column deformability. Tests on full-scale reinforced concrete columns have shown that, where the deformability of existing columns is limited to 1% to 2% drift ratio, depending on the mode of behavior, once retrofitted with the Retro-Belt™ retrofitting system, the columns could sustain 4% drift or higher without any significant damage or decay in moment capacity.

The Retro-Belt™ retrofitting system offers a practical alternative for retrofitting reinforced concrete columns in buildings and bridges. It has certain distinct advantages over other retrofit systems; notably, it is based on active as well as passive confinement pressure, whereas other systems rely on passive pressure only. Furthermore, the installation process does not require any heavy equipment - a team of two workers is able to install the belts and apply the post-tensioning by means of hand held jacks. Because the Retro-Belt™ retrofitting system is quick and easy to install, it is an inexpensive alternative to other retrofit systems and should be less intrusive to building occupants or to roadway traffic.

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Introduction

The performance of reinforced concrete columns during recent earthquakes has clearly demonstrated the possible failures associated with inadequate transverse reinforcement. The transverse reinforcement requirements of older codes were less stringent than those of present standards. Hence many of the reinforced concrete columns built prior to the early 1970’s could experience the same failures as those seen in recent earthquakes.

A new retrofitting technique was developed and tested at the University of Ottawa, Canada, which involves external prestressing of columns by means of individual hoops (Saatcioglu and Yalcin, 2001; Saatcioglu et al., 2000; Yalcin, 1997; Mes, 1999; Beausejour, 2000).

Column Retrofit Solution

Transverse reinforcement in reinforced concrete (R/C) columns fulfils three main functions: restraining longitudinal reinforcement against buckling; increasing shear resistance; and confining concrete for improved deformability. Lateral confinement also improves bond between steel and concrete, playing a crucial role on the performance of spliced longitudinal reinforcement. The Retro-Belt™ retrofitting system externally applies a lateral prestressing force, which improves all three mechanisms, enhancing strength and deformability of concrete columns. The system consists of specially designed anchors, which hold the stress in prestressing strands that are placed as individual hoops at design spacing and prestress level. The active pressure provided translates into reduced material consumption. Furthermore, because the prestressing strands are placed as individual hoops, they do not significantly increase the column stiffness. The new retrofit system offers flexibility in design in terms of the spacing and stress level of the hoops, and can be adapted to any column size. It can be designed to achieve the desired level of performance in the column. For columns with square and rectangular cross-sections, a system of raisers is used to ensure that the active pressure from the strands is well distributed along each column face.

Column Retrofit Research

An experimental investigation of the Retro-Belt™ retrofitting system was conducted at the University of Ottawa. In total, 19 large-scale R/C columns were tested under simulated seismic loading. The test columns were designed to investigate shear-dominant and flexure-dominant columns, as well as the problems associated with lap-splices. The columns had circular or square cross-sections; different aspect ratios; continuous or lap-spliced longitudinal bars; and different retrofitting arrangements (prestress levels and spacing). Control columns and retrofitted columns were designed and built based on pre-1970’s practice. Notably, the transverse reinforcement (typically #3 or #4 bars – 10M was used in tests) was placed at 300mm (12”) spacing; and the length of the lap-splice starter bars was 20 times the longitudinal bar diameter.

Column Test Results – Shear-Dominant R/C Columns

Shear-dominant R/C columns often have a low aspect ratio (short shear span and large cross-section), and are subjected to high levels of shear forces. These columns can not develop
their full flexural capacity, showing premature failure due to diagonal tension and/or diagonal compression. Shear failure is a brittle form of failure, occurring with rapid strength degradation – this type of failure should be avoided in practice.

In the first phase of the experimental research (Yalcin, 1997), which was conducted to investigate shear-dominant columns, the control columns failed in a brittle manner. The failure was sudden and was associated with lack of transverse reinforcement. A photograph of the circular control column, BR-C1, is shown in Fig. 1 at failure. The basic rationale behind providing external prestressing as the column retrofit technique was to make up for this deficiency in transverse reinforcement by effectively adding an adequate amount of transverse steel to the exterior of the column, while also improving diagonal tension resistance of concrete.

The initial prestress in the strands reduced inclined crack widths and improved the mechanism of aggregate interlock, thereby increasing shear resistance of cracked concrete. Once the active lateral pressure had been overcome by increased shear, the strands then behaved as shear reinforcement, adding to the diagonal tension resistance. When the diagonal tension failure was eliminated, the strands also helped improve the ductility of compression concrete through confinement. The net effect was to suppress premature shear failure and promote ductile flexural behaviour. A photograph of the retrofitted column, BR-C2, is shown in Fig. 1 at 5% drift. The Retro-Belt™ retrofitting system confined both the cover and core concrete, which increased the column deformability and its energy dissipation capacity. For the test specimens, the drift capacity was improved from 1% for the control columns to at least 4% for the retrofitted columns. This significant improvement is shown in Fig. 1, where the envelope of the hysteresis loops for columns BR-C1 and BR-C2 are compared.

**Column Test Results – Flexure-Dominant R/C Columns**

Flexure-dominant columns have a higher aspect ratio (longer shear spans), and are subjected to higher flexure. These columns first develop their flexural yield, prior to any distress in shear. Flexural yielding is associated with the yielding of longitudinal reinforcement; therefore, these columns have a ductile behaviour that results in gradual strength decay.
In earthquake resistant design, where inelastic deformations are relied on for energy dissipation, it is desirable to promote this flexural mode of response. Although flexural behaviour is generally ductile, it may become brittle if dominated by compression concrete. In such cases, the behaviour of concrete, and hence the entire column can only be improved by increasing confinement.

Although flexure dominant members generally exhibit improved deformability, columns under combined axial compression and flexure may show limited ductility, especially under cyclic loading.

Retrofitting flexure-dominant columns with the Retro-Belt™ retrofitting system improves concrete confinement (Mes, 1999). Photographs of the control column BR-C6 at failure, and the retrofitted column BR-C7 at 5% drift, are shown in Fig. 2. A maximum hoop spacing of approximately one quarter of the column cross-sectional dimension was adequate to provide the required confinement, hence improving ductility. For larger size columns \( h > 600 \text{mm}, \) where \( h \) is the outside dimension of the column, a maximum spacing of 150 mm is suggested to assure good stress distribution and proper confinement. For the test specimens, the drift capacity was improved from 2% for control columns to at least 4% to 5% for the retrofitted columns. This improvement is shown in the graph of Fig. 2, where the envelope of the hysteresis loops of columns BR-C6 and BR-C7 are compared.

Column Test Results – R/C Columns with Lap-Splice

Reinforced concrete columns that have lap-spliced longitudinal reinforcement may not perform adequately if these lap-splices are short and placed within the plastic hinging region. The columns may not develop their full flexural capacity and usually fail due to the bond failure and slippage of splices, thus further reducing the lateral load capacity of the column. Columns with lap-spliced longitudinal reinforcement have a different failure mechanism than columns with continuous longitudinal bars. Columns with continuous longitudinal bars develop a yielding and buckling mechanism in the bars; whereas, the lap-spliced bars lose their bond once the level of strain is too high and the bars develop a slip mechanism – typified by an excessive

![BR-C6 at failure](image1)
![BR-C7 at 5% drift](image2)

Figure 2. Test photographs and envelope of hysteresis loops (Mes, 1999).
rotation at the column/footing interface.

The tested control columns did not reach their flexural capacity and failed due to the reinforcement slippage. The drift capacity of both the flexure dominant and the shear dominant control columns was limited to 1%. Once retrofitted with the Retro-Belt™ retrofitting system, the columns no longer had a problem associated with bar slip and performed in a ductile manner. The concrete strain was limited and the concrete/steel bond was maintained because of the clamping forces coming from the prestressing hoops. Note that the spacing and prestress levels were designed to attain the desired clamping force within the lap splice region (Beausejour, 2000).

For the test specimens with lap-splices, the drift capacity was improved from 1% for the control columns to at least 4% for the retrofitted columns. The test results of the flexure dominant columns with a rectangular cross-section are shown in Fig.3. Photographs of the control column BR-S5 at failure, and the retrofitted column BR-S6 at 5% drift, are shown in Fig. 3. The improvement in flexural and drift capacity is shown in the graph of Fig. 3, where the envelope of the hysteretic loops of columns BR-S5 and BR-S6 are compared.

![Figure 3. Test photographs and envelope of hysteresis loops (Beausejour, 2000).](image)

**Design Guidelines**

An overview of the design procedure for the Retro-Belt™ retrofitting system is outlined in the following section to demonstrate the basic design principles.

**External Prestressing for Improved Shear Resistance**

To retrofit shear deficient columns by external prestressing, the level of prestressing, hoop spacing and strand size must be determined. This transverse prestressing can enhance both the concrete and reinforcement shear resistance in order to achieve the performance level expected from the structure.
Designing for prevention of shear damage ensures a more desirable failure mechanism with improved energy dissipation during a seismic event. After the earthquake, the column is not likely to require any repair due to shear damage. This is achieved by providing sufficient transverse prestressing against diagonal tension so that the widths of diagonal cracks are controlled and the deterioration of concrete under stress reversals is not permitted. Transverse prestressing to eliminate diagonal cracking completely may not be necessary, as some tension in concrete can be tolerated for an acceptable level of performance.

The following requirements are intended to maintain the integrity of concrete during seismic response while providing reserve shear capacity beyond the development of effective prestress. The transverse strain level is restricted to 0.2% so that both concrete and internal reinforcement can be relied on for shear resistance.

The seismic shear capacity, \( V_e \), of a reinforced concrete column, retrofitted by external prestressing, consists of contributions from concrete, \( V_c \), internal shear reinforcement, \( V_s \), and external prestressing, \( V_p \), as indicated below. The shear capacity of the column, \( V_e \), should be higher than the maximum seismic shear force that the column may be subjected to during an earthquake. This is determined as the larger of the factored shear force and the shear force associated with the formation of flexural plastic hinges in the column.

\[
V_e = \phi V_c + \phi V_s + \phi V_p
\]

\[
V_p = 2 \cdot A_{ps} \cdot \left( f_{pi} + 0.002E_p \right) \cdot \frac{h}{s_{ps}} \quad \text{where}: \quad s_{ps} \leq \frac{h}{4}
\]

\[
\text{and} \quad 50 \text{ MPa} < f_{pi} \leq 0.5 \ f_{pu}
\]

In these equations, \( V_e \) and \( V_s \) are as defined in ACI 318 Building Code (1999). The symbol \( \phi \) indicates that the shear forces have the appropriate strength reduction factors as applied to concrete, reinforcing steel, and prestressing steel. \( A_{ps} \) is the cross-sectional area of the prestress strands; \( f_{pi} \) is the initial prestress applied to the strands; \( f_{pu} \) is the ultimate strength of the strands; and \( s_{ps} \) is the strand spacing. The term 0.002 \( E_p \) is the increase in strand stress during response to seismic action due to increased transverse strain (limited to 0.2% as explained above), where \( E_p \) is the Modulus of Elasticity of the prestressing strand. The symbol \( h \) is the outside cross sectional dimension of the column.

In Eq. 1, the contribution of axial compression to concrete shear resistance is neglected, conservatively. Note that, in the plastic hinge region, the contributions of concrete to shear resistance may not be reliable. This is especially true if diagonal tension is not well controlled, unlike transversely prestressed columns. These columns are often designed with \( V_c = 0 \) as per ACI 318 (1999) requirements. If the factored axial force results in net tension in the column, \( V_c \) may not be reliable either, and should be taken as zero. The contribution of transverse shear reinforcement in most existing columns, with large tie spacing and lapped tie ends may not be reliable within the plastic hinge region. This quantity, \( V_s \), may have to be taken as zero, for a conservative retrofit design.
Shear Retrofitting Design Procedure

1. Check if \(\phi V_c + \phi V_s > V_{prob}\), where \(V_{prob}\) is the probable shear force, defined below.

2. \(V_{prob} = \frac{M_{prob}}{L}\), where \(L\) is the shear span and \(M_{prob}\) is the probable moment resistance - nominal moment capacity with 1.25 factor for longitudinal steel yield strength.

3. If \(\phi V_c + \phi V_s > V_{prob}\) and the transverse reinforcement conform to the seismic detailing requirements, no shear retrofit is needed.

4. If \(\phi V_c + \phi V_s < V_{prob}\), then shear retrofit is needed.

5. If retrofitting, satisfy: \(\phi V_c + \phi V_s + \phi V_p > V_{prob}\).

6. In the plastic hinge region take \(V_c = 0\)

7. In the plastic hinging region, \(V_s\) should be taken as zero if the internal ties do not meet the seismic detailing requirements of the current building code (ACI 318 1999).

8. Check requirements for confinement and lap-splice design.

External Prestressing for Improved Confinement

Whether a column is initially shear or flexure dominant, in order for it to achieve a ductile behaviour, the core concrete must be properly confined, especially in the plastic hinge region. The plastic hinge region is typically equal to the outside cross-sectional dimension, \(h\), of the column. While confinement of compression concrete is essential for increased flexural deformability, shear dominant columns often change their failure mode to flexure after being retrofitted for shear. Saatcioglu and Razvi (2001) suggested the following design expressions for column confinement in new construction, based on a displacement based design procedure.

\[
A_{sh} = 14 \cdot s \cdot h_c \cdot \frac{f_c'}{f_s} \left( \frac{A_c}{A_e} - 1 \right) \cdot \frac{\bar{d}}{\sqrt{k_c}} \cdot \frac{P_f}{P_{ro}}
\]

where:

\[
\frac{A_c}{A_e} - 1 \geq 0.3
\]

\[
\frac{P_f}{P_{ro}} \geq 0.2
\]

and

\[
k_c = 0.15 \sqrt{\frac{h_c}{s}} \quad \text{for rectangular cross-section}
\]

\[
k_c = 10 \quad \text{for circular cross-section}
\]

In Eq. 3, \(A_{sh}\) is the total area of transverse reinforcement in a given cross-sectional direction; \(s\) is the tie spacing; and \(f_s\) is the steel stress in the ties. \(A_c\) is the core area of the column and \(h_c\) is the core dimension, both taken from centreline to centreline of the perimeter ties. \(A_e\) is the gross area of the column and \(f_c'\) is the cylinder strength of concrete. \(P_f\) is the factored axial compressive force of the column and \(P_{ro}\) is the concentric load resistance of the column. The symbol \(k_c\) is the confinement efficiency coefficient, as defined in Eq. 3; and \(s\) is the spacing of laterally supported longitudinal reinforcement. The design drift ratio, \(\delta\), depends on the level of performance expected from a column during a seismic activity. Recent codes suggest a design drift level of 2.0% to 2.5% for new construction. For retrofitting, a higher design drift level may be more appropriate and can be achieved without much difficulty and additional cost. A minimum design drift level of 4% is recommended for column retrofit design.
Drawing a parallel between the passive confinement pressure induced by non-prestressed hoop reinforcement and the active and passive confinement pressures induced by prestressing strands, one can derive a design expression for retrofitting concrete columns. The principle of retrofitting a column for confinement then becomes achieving the required confinement pressure by external prestressing. An important design parameter here is the level of stress in the strands when the maximum column capacity is attained, which in turn is a function of the ability of concrete to expand laterally. Saatioglu and Razvi (2001), based on experimental observations, recommended a conservative limit of 600 MPa stress in transverse reinforcement, which corresponds to 0.3% strain, although they have observed experimentally that the transverse steel stresses could be as high as 1000 MPa when the confinement efficiency was very high. The same transverse strain limit ($\varepsilon_t = 0.3\%$) can be used to derive an equation for retrofitting.

It should also be noted that Eq. 3 was derived for conventional hoop reinforcement used in new construction. This reinforcement is used to confine the core concrete, and the required steel amount is a function of cover-to-core area ratio ($A_g/A_c - 1 \geq 0.3$). This ratio was limited to 0.3 for columns with a small area of cover concrete relative to the core area (as in the case of bridge columns with large cross-sectional areas). When a column is retrofitted using the external prestressing technology, the entire cross-sectional concrete is confined, including the cover concrete. Adopting these limits, $A_g/A_c - 1 = 0.3$ and $\varepsilon_t \leq 0.3\%$, an equation can be derived to calculate the required area of prestressing steel for column confinement. For circular columns:

$$A_{ps} = 2.1 \cdot \frac{f_c'}{f_{ps} + \varepsilon_t \cdot E_p} \cdot h \cdot s_{ps} \cdot P_f \cdot P_{ro}$$

where: $\frac{P_f}{P_{ro}} \geq 0.2$ and $\varepsilon_t \leq 0.003$

also, $s_{ps} \leq \frac{h}{4}$ or 150 mm

and $50$ MPa $< f_{ps} \leq 0.5 \cdot f_{pu}$

(4)

The symbols of Eq. 4 are as defined above, for Eqs. 2 and 3. The same principle applies to columns with rectangular cross-sections. Since the recommended retrofit procedure includes continuous steel hoops with raisers, which apply near uniform lateral pressure along the section perimeter, the behaviour would be similar to that of circular columns developing uniform hoop tension. In this case, the pressure on the longer side of rectangular section governs the design.

**Confinement Retrofitting Design Procedure**

1. Determine if retrofit is required by checking the existing confinement reinforcement against that required by Eq. 3.
2. If retrofit is required, design strand size, spacing and prestress level. Note that the contribution of internal ties should only be included if appropriate.
3. Confine the plastic hinge region by means of the Retro-Belt™ retrofitting system, over a height (measured from the critical section for flexure) equal to $1.5h$, where $h$ is the outside dimension of the column, but not less than $L/4$, where $L$ is the shear span.
4. The spacing limit for the strands may be relaxed by a factor of 2 within a region $1.5h$ to $2h$ (from the critical section for flexure).
External Prestressing for Improved Lap-Splice Performance

Lap-splices that cause problems are those that are too short and located within the plastic hinge region. It was experimentally observed that (Saatcioglu et al., 2000; Beausour, 1999; Priestly & Seible, 1991) lap-splice failures occurred when the transverse tensile strains exceeded 0.1% to 0.2%. Therefore, retrofitting for insufficient lap splices should be based on the concept of limiting transverse tensile strains in concrete. This can be achieved by means of external prestressing, in much the same manner as for confinement by external prestressing. The design equations and the design procedure are the same as for confinement, except for the transverse tensile strain limit, which can be set conservatively at 0.1% in the lap-splice region ($\varepsilon_t \leq 0.001$). The prestressing strands are required over the entire lap length.

The experimental observations used to generate the design information is based on tests of columns with a lap splice length of $20d_b$ in the hinging region, where $d_b$ is the longitudinal bar diameter. For lap lengths greater than this quantity, lap-splice failure would be less critical. Hence, the use of $20d_b$ for such cases would be a conservative extension of the test data. The procedure is yet to be verified for lap length smaller than $20d_b$.

Lap-Splice Design Procedure

1. If retrofitting is required use Eq. 4 with $\varepsilon_t \leq 0.001$ to find the strand area, spacing and prestress level. Contribution of internal ties should only be included if appropriate.
2. Confine the entire lap-splice region. This region need not be longer than $20d_b$. Columns with lap lengths shorter than $20d_b$ may require more stringent confinement.

Summary and Conclusions

A new seismic retrofit technique, the Retro-Belt™ retrofitting system, was developed as a result of extensive experimental research at the University of Ottawa. Tests of 19 large-scale columns, under simulated seismic loading, indicated that column deformability could be improved significantly by the application of the new retrofit technique. The technique is based on external prestressing of concrete columns with shear, confinement and reinforcement splice deficiencies in transverse direction. The prestressing is done by individual steel strands and specially designed anchors, forming individual hoops. The results indicate that the retrofitting system successfully improved column ductility and increased the drift ratio capacity beyond 4%.

A design procedure was developed based on the principles of mechanics and experimental findings. Much of the design methodology and principles are congruent with findings from other researchers and new code requirements. The basic design principle is to retrofit an existing column to make it conform to the code requirements for new structures. Depending on the retrofit requirements and project details, the Retro-Belt system may prove to be an economical and a technically sound solution in many seismic retrofit projects.

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Notation

\( A_c \) : Cross-sectional area of core concrete, measured centre-to-centre of perimeter hoop (mm\(^2\)).
\( A_g \) : Gross cross-sectional area of column (mm\(^2\)).
\( A_{ps} \) : Area of prestressing strand used to prestress column in the transverse direction (mm\(^2\)).
\( A_{sh} \) : Total area of transverse reinforcement within spacing, \( s \), in the direction of shear force (mm\(^2\)).
\( d_b \) : Diameter of longitudinal bar (mm).
\( E_p \) : Modulus of elasticity of prestressing steel (\( E_p = 200000 \) MPa).
\( f_c' \) : Compressive strength of concrete, as determined from standard cylinder tests (MPa).
\( f_{pi} \) : Initial prestress level in strands (MPa).
\( f_{pu} \) : Ultimate strength of prestressing strand (MPa).
\( f_s \) : Stress in transverse shear reinforcement (MPa).
\( h \) : Column sectional dimension parallel to shear force, or circular section diameter (mm).
\( h_c \) : Concrete core dimension, measured centre-to-centre of perimeter hoop (mm).
\( k_c \) : Transverse reinforcement confinement efficiency coefficient, as defined in Eq. 3.
\( L \) : Column shear span (mm).
\( P_f \) : Factored axial compressive force (N).
\( P_o \) : Concentric compressive strength of column (N).
\( P_{ro} \) : Factored axial load resistance (N).
\( M_{prob} \) : Probable moment – nominal moment with 1.25 factor for longitudinal steel yield strength (Nmm).
\( s \) : Spacing of transverse shear reinforcement along height of column (mm).
\( s_l \) : Spacing of laterally supported longitudinal reinforcement (mm).
\( s_{ps} \) : Spacing of external prestressing hoops (mm).
\( V_c \) : Shear force resistance provided by tensile stresses in the concrete (N).
\( V_e \) : Effective shear capacity of retrofitted column (N), as defined in Eq. 1.
\( V_p \) : Shear strength enhancement provided by external prestressing (N).
\( V_{prob} \) : Probable shear, calculated as \( M_{prob} / L \) (N).
\( V_s \) : Shear resistance provided by internal shear reinforcement (N).
\( \delta \) : Design drift demand level.
\( \varepsilon_t \) : Transverse strain.

References


