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Development of plastic hinge length expression for fiber reinforced polymer strengthened concrete bridge pier

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ABSTRACT: This paper focuses on the development of plastic hinge length expression for Fiber Reinforced Polymer (FRP) strengthened concrete bridge pier under combined axial and reverse cyclic loading using finite element modeling approach. In a high seismic event, a bridge pier might experience in elastic deformations which in turn could lead to developing plastic hinge regions. Bridge piers are designed in such a way so that this kind of scenario occurs away from the superstructure. The severity of this phenomenon depends on the characteristics of the seismic event and the structural details of the pier as well. Data observed from past seismic events indicate that these ground motions contain a huge surge of energy which can make considerable damage to our existing bridge structures. In order to minimize this damaging of the structures and to save the human lives, the bridge piers might require proper strengthening to withstand such a huge amount of energy exerted by the ground motions. FRP can be considered for strengthening purposes due to its relatively easy and quick installation feature. In this paper, combined axial and reverse cyclic loading have been performed to predict the nonlinear behavior of FRP strengthened concrete bridge piers and expression for calculating the plastic hinge length has been developed. Different configurations of FRP strengthened concrete bridge piers have been tested using finite element analysis and damage propagation and strain distribution have been analyzed to calculate plastic hinge length using an analytically developed equation.

1 INTRODUCTION

The pier of a bridge is the most valuable element of a bridge system to transfer the incoming loads from the vehicles but also the most endangered part of a bridge in the event of an earthquake. Because it goes through a plastic deformation when a cyclic load is been applied to it. This plastic deformation is located in an area called plastic hinge region which encounters concentrated damage (Mortezaei & Ronagh, 2012). So, the need for predicting the plastic hinge length for the bridge pier is necessary to know the critical regions that need to be confined with FRP. Many researchers in the past have used existing equations to estimate the plastic hinge length (Muntasir Billah & Shahria Alam, 2012; O'Brien et al., 2007). This particular study aims to develop an expression that can evaluate the length of the plastic hinge of FRP confined bridge pier with the help of numerical simulation software ABAQUS.

Plastic hinges form at the regions where the maximum moment occurs in an RC column. This large moment causes significant damage to the pier in those regions and results in catastrophic failure of a structure (Bae & Bayrak, 2008). The plastic hinge region experiences inelastic curvature which is assumed to be constant over the plastic hinge length. So, the integration of curvature will result in the plastic hinge length if the tip displacement is known and vice-versa. The relation of sectional level response and member level response largely depends on assessing the plastic hinge length accurately. Previously numerous researchers have focused on assessing the plastic hinge length of RC columns. But the location and length of the plastic hinge will largely differ for FRP confined bridge pier from that of RC columns only. Many factors affect the length of the plastic hinge, such as concrete strength, level of axial load, level of shear stress in the plastic hinge region, moment gradient, mechanical properties of longitudinal and transverse reinforcement, level of confinement and its effectiveness in the potential hinge region. Many scholars have proposed various equations that can be used to measure the plastic hinge length of the concrete members. The calculation of the plastic hinge length using the expressions that have already been published differs greatly and the expressions have been

developed taking into account various parameters. Since the FRP confined bridge pier shows superior seismic efficiency, accurate determination of the equation for the plastic hinge length is very important.
The feasibility of the use of FRP in civil engineering structures has been investigated by Bank (2006) and reported thatthe cost of large-scale use of FRP is higher than that of conventional materials. The use of FRP will increase the initial cost of the construction significantly, but the confinement provided by the FRP will increase the flexibility of the structure against possible hazardous incidents which could transmit dynamic loading to the structure.

Many researchers have come up with simplified equations that do not contain most of the aforementioned factors which result in large variations in the value of plastic hinge length. Bae & Bayrak (2008)have considered the effects of axial load, shear-span ratio and amount of longitudinal steel except the strength of concrete and mechanical properties of reinforcement in the calculation of plastic hinge length. Berry et al have studied the same issue and included the effects of strength of concrete and properties of reinforcement but excluded the other parameters. Although, numerous researchers (A.Sheikh & Shafik S.Khoury, 1993; Bae, 2005; Park et al., 1982; Priestley & Park, 1987) have investigated the plastic hinge length for concrete columns. However, (Atalay & Penzien, 1975; Tanaka & Park, 1990)reported behavior that shows plastic hinge length increases with increased axial load. Therefore, consideration of the impact of axial loading is important in the study of plastic hinge length expression for FRP confined bridge pier. This study focuses on three different parameters of axial loading magnitude, longitudinal reinforcement ratio, and aspect ratio to derive the equation for plastic hinge length. In order to achieve the goal, four different axial load levels, three different longitudinal reinforcement ratio, and two different aspect ratios of bridge pier were taken into account.

2 DESIGN AND GEOMETRY OF BRIDGE PIER

The design and geometry of the bridge pier wrapped with FRP is described in this section. Figure 1shows the cross section of the column where the diameter (d) of all the columns were fixed to be 1.83m, 48-29mm diameter longitudinal reinforcement and 16mm diameter spirals at 76 mm pitch were used. For the parametric study, three different longitudinal reinforcement ratios ρ_s, 1.2%, 2%, 3% and a fixed 0.61% of spiral reinforcement ratio were used. Two different thickness (t_f) of FRP sheet were used for the bridge pier (1.5mm and 10mm). Detailed material properties of concrete and reinforcement are summarized in Table 1.

Table 1. Material properties for FRP wrapped bridge pier.

Material	Property	Value
Concrete	Compressive Strength (MPa)	34.5
	Corresponding strain	0.0029
	Tensile Strength (MPa)	3.5
	Elastic modulus (GPa)	23.1
Steel	Elastic modulus (GPa)	200
	Yield stress (MPa)	475
	Ultimate stress (MPa)	692
	Ultimate strain	0.14
FRP	Longitudinal elastic modulus (GPa)	153
	Transverse elastic modulus (GPa)	10.3
	Major Poisson's ratio	0.3
	Shear modulus (GPa)	6
	Ultimate longitudinal tensile strength (MPa)	2537
	Ultimate longitudinal compressive strength (MPa)	1580
	Ultimate transverse tensile strength (MPa)	82
	Ultimate transverse compressive strength (MPa)	236
	Ultimate in-plane shear strength (MPa)	90

3 FINITE ELEMENT MODELING

The computational analysis of FRP enclosed concrete bridge piers under simultaneous axial and cyclic loading was carried out with the aid of the commercial finite element software ABAQUS v6.14. The model contains the basic elements of the ABAQUS/Explicit system (ABAQUS, 2014). The concrete was modeled using eight-node solid elements with reduced integration (C3D8R). These elements have three degrees of freedom per node and reduced integration to calculate the stresses and strains in the elements. The C3D8R elements are computationally useful for modeling concrete cracking (T. Mustafyet al., 2019). Four node shell element

S4R was adopted to model the FRP wrapping of the concrete members. These elements have: (i) six degrees of freedom per node, and (ii) reduced integration in the plane of the elements, and (iii)five-section points to compute the stress and strain variations through the thickness. The rebars were modeled using the two-node three-dimensional truss element (T3D2). These can take an axial stretch, bending, torsion in 3D space. The property modeling of concrete was done by implementing a concrete damaged plasticity model that includes compression hardening and tension stiffening of concrete definitions. The CDP model proposed by(Han et al., 2007; Tao et al., 2013) was used to model the concrete. The damaged parameter was calculated by the proposed model of (Ding et al., 2017). The steel rebars and stirrups were both modeled as isotropic elasto-plastic material satisfying the von Mises yield criterion (T. Mustafyet al., 2018). Elastic property of FRP materials was assumed to be lamina in ABAQUS/Explicit and to predict the damage after peak strength (T. Mustafyet al., 2010). Hashin Damage variables were used where the fibers of the FRP sheets were assumed to be unidirectional.

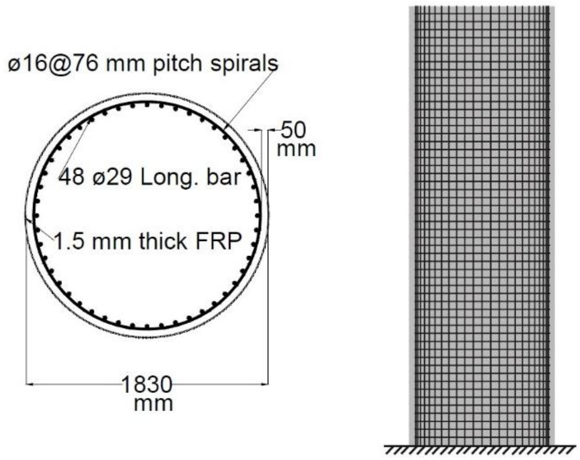

Figure 1. Cross section and elevation of FRP wrapped concrete bridge pier.

4 VALIDATION OF NUMERICAL RESULTS

The parametric study of bridge pier was followed by validation of FRP wrapped reinforced cylinders with the test results conducted by Parretti & Nanni (2002), for axial compression. The material properties used by Parretti & Nanni (2002),are summarized in Table 2where two different concrete strength and four different thicknesses of FRP sheet were used. For all the circular sections, 200mm cross section, 914 mm height, 8ϕ10 longitudinal reinforcement and ϕ6@50mm lateral ties were used for all the samples. Figure 2 shows typical axial load (kN) vs. axial displacement curve of FRP wrapped section generated by numerical simulations. Table 3 shows the comparison of axial load carrying capacity of FRP wrapped cylinders found from experimental and numerical results.

Table 2. Material properties of FRP wrapped columns.

Column	Concrete	Longitudinal Steel	Lateral steel	FRP		
	f'_c	f_y	f_y	t_f	f_{fu}	E_f
	MPa	MPa	MPa	mm	MPa	GPa
CF-130	23.8	360	632	0.165	3800	227
DB450-C	25.5	393	517	0.27	1689	125.6
L200-C	25.5	393	517	0.122	4140	230
L300-C	25.5	393	517	0.175	4090	230

Table 3. Comparison of axial load carrying capacity.

Column	P_{ex} kN	P_{num} kN	P_{ex}/P_{num}
CF-130	1356	1468	0.92
DB450-C	1236	1342	0.92
L200-C	1543	1492	1.03
L300-C	1542	1497	1.03

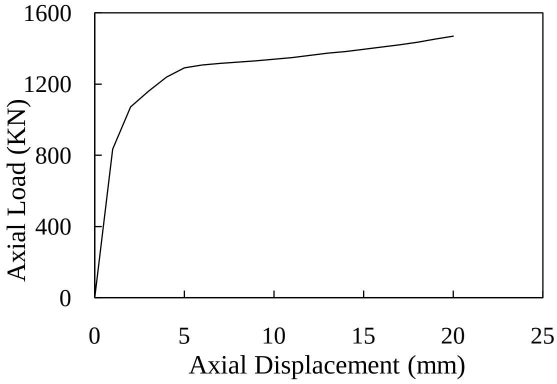

Figure 2. Axial load vs. axial displacement curve of CF-130.

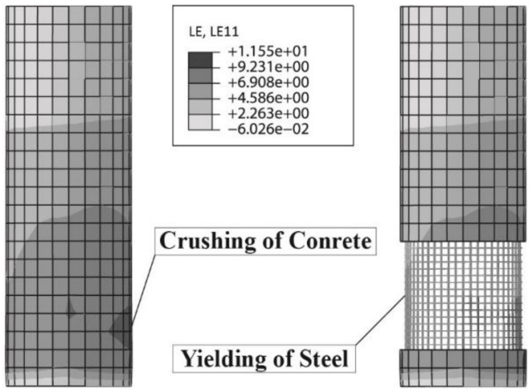

Figure 3. Strain contour of concrete and longitudinal steel.

5 NUMERICAL METHOD TO PREDICT THE PLASTIC HINGE LENGTH

By definition, plastic hinges form where maximum moment is generated within the column. But identifying the position of the maximum moment is quite difficult numerically. As bridge pier with large diameter and length with FRP wrapping is very costly to be analyzed experimentally and many parameters are involved to form plastic hinge length, this study focused on developing the expression for plastic hinge length by numerical method.

In practical scenarios, when an earthquake hits a bridge pier, the pier experiences lateral displacement while supporting the gravity load already imposed on it. The damage of the concrete and yielding of longitudinal reinforcement is closely related to the length of plastic hinge (Billah & Alam, 2014).The crushing of concrete and yielding of reinforcement occurs at the compression side of the pier. The damage of concrete and yielding of longitudinal reinforcement can be identified by tracking the strain profile of the materials along the height of the pier. The strain of concrete and reinforcement increase with the increase in lateral displacement. This study analyzed the pier under four different axial load levels and lateral load protocol demonstrated in Figure 4. Typical lateral load vs lateral displacement curve is shown in Figure 5.

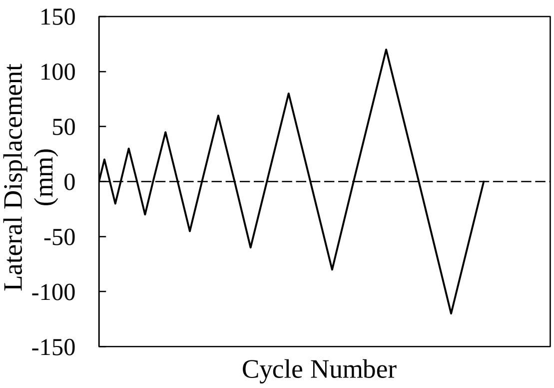

Figure 4. Lateral load protocol.

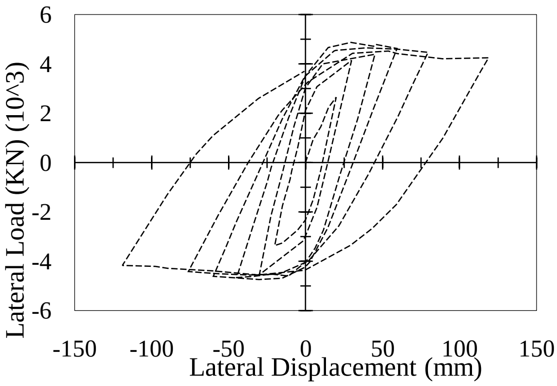

Figure 5. Lateral load vs. lateral displacement curve of FRP wrapped bridge pier.

Three types of wrapping position of FRP sheet were studied in this study to investigate the influence of FRP wrapping length and positioning on the plastic hinge length formation. The main aim of a bridge pier is to keep away the damage from the superstructure. In this study, three types of position included full length wrapping, 0.33h wrapping in the middle, 0.25h wrapping at the both ends. In Figure 6, maximum damage happens at 0.24h from the bottom of the pier when the pier is fully wrapped for both concrete and longitudinal reinforcement. In case of 0.33h wrapping in the middle and 0.25h wrapping at the ends, the maximum damage occurs at 0.22h and 0.33h height of the pier respectively. For all the cases, axial load, aspect ratio, longitudinal reinforcement ratio and thickness of FRP were kept constant. As FRP sheets provides confinement to the concrete, the maximum damage shifts away from the confinement regions to unconfined regions. Due to fixed condition at one end of the column, a length of 0.04h from the bottom remained undamaged. As a result, the plastic hinge length is calculated by subtracting the undamaged length.

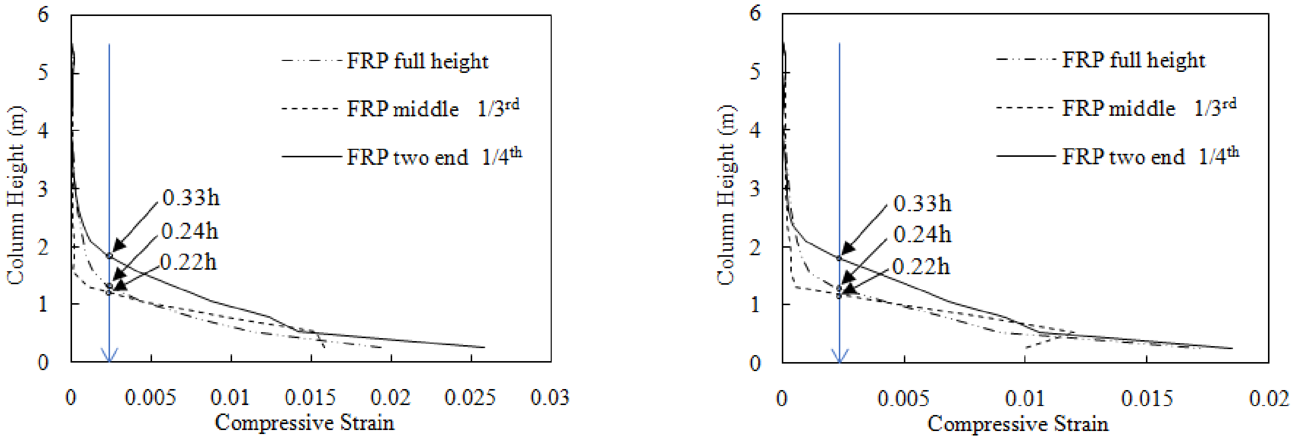

Figure 6. Effect of different positions of FRP wrapping on core concrete and longitudinal rebar strain profiles.

5.1 *Effect of Axial Load*

The study of the effect of different axial load levels on the formation of plastic hinge length was conducted with the aspect ratio, longitudinal reinforcement ratio and thickness of the FRP keeping constant. There were four different axial load levels (5%, 10%, 20%, 30%) that were considered during the study. The longitudinal reinforcement ratio of 1.2%, aspect ratio of 3 and 1.5mm thick FRP was used. Figure 7 shows the variation of strain profile along the height of the bridge pier in the core concrete and longitudinal reinforcement. It can be seen that the strain profile changes quickly at the height where the plastic hinge form. This region experiences significant damage due to seismic load. From the figure, it is evident that the increase in axial load level decreases the strain in core concrete and longitudinal reinforcement. A gradual improvement in strain can be observed as the load level is increased from 5% to 10% for both core concrete and longitudinal reinforcements. This shift does not differ significantly leading to a further increase in the load level. The crushing of concrete and yielding of reinforcement is used to determine the height of the plastic hinge. The plastic hinge length varies between 0.17h to 0.21h for various axial load levels where h is the length of the bridge pier.

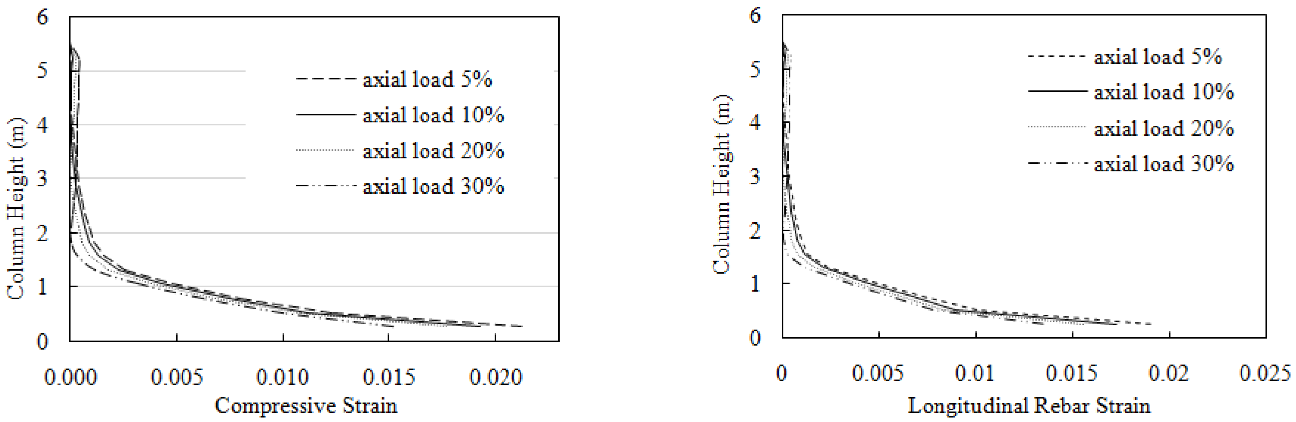

Figure 4. Effect of axial load on core concrete and longitudinal rebar strain profiles.

5.2 *Effect of Longitudinal Reinforcement Ratio*

To study the effect of longitudinal reinforcement ratio on the formation of plastic hinge length, three different reinforcement ratio (1.2%, 2%, 3%) was used. For all the cases the axial load level, aspect ratio and thickness of the FRP was kept constant. The axial load of 10%, aspect ratio of 3 and 1.5mm thick FRP was used during all three-reinforcement ratio analysis. Figure 8shows that, strain profile of core concrete doesn't change much at the plastic hinge region when longitudinal reinforcement ratio is increased. But for longitudinal reinforcement, the strain drastically decreased with the increase in reinforcement ratio. From the figure, it is certain that the length of the plastic hinge decreases with the increase in the longitudinal reinforcement ratio. The plastic hinge length varies from 0.18h to 0.20h for different longitudinal reinforcement ratio. It also evident from the figure that increase in longitudinal reinforcement ratio decreases the overall strain of both concrete and reinforcement along the height of the bridge pier. This indicates higher strain capacity can be achieved by increasing the reinforcement ratio. A comparison between the strain profile of concrete and longitudinal steel can be seen in Figure 9 at higher reinforcement ratio of 3%.

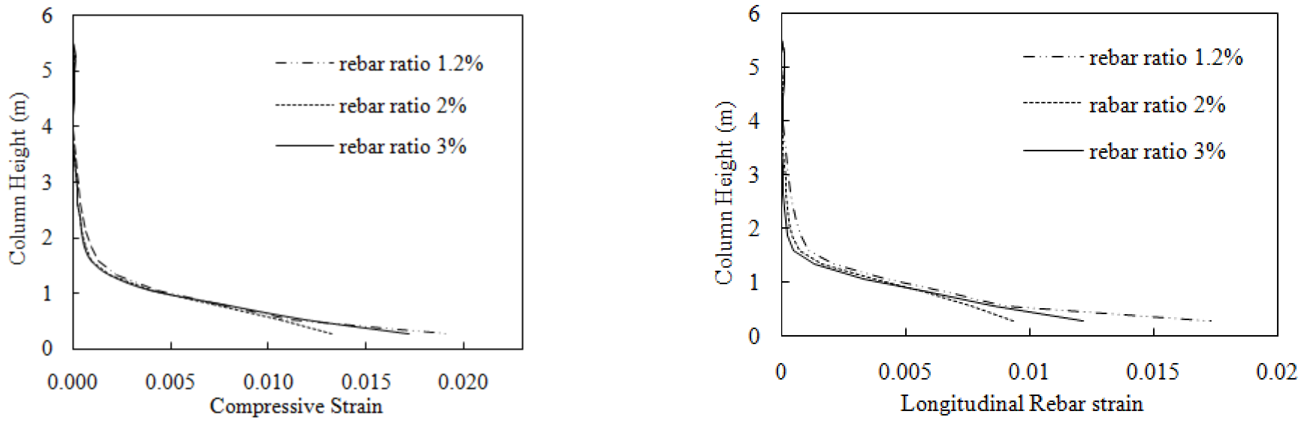

Figure 8. Effect of reinforcement ratio on core concrete and longitudinal rebar strain profiles.

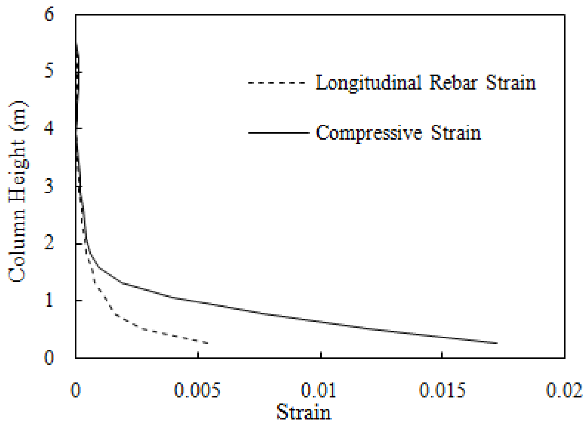

Figure 5. Comparison of strain profile of concrete and longitudinal rebar at higher reinforcement ratio.

It is evident from the figure that the plastic hinge length of concrete develops much higher than longitudinal reinforcement when higher reinforcement ratio is used.

5.3 *Effect of Aspect Ratio*

Various researchers have found that the length of plastic hinge is greatly influenced by the aspect ratio of the (l/d) of the column. In order to find the actual scenario for FRP confined bridge pier, two aspect ratios were studied to (l/d=3 & l/d=5). For both of the cases a fixed axial load of 10%, longitudinal reinforcement ratio of 1.2% and 1.5mm thick FRP was used. The effect of these two aspect ratios on the strain profile of core concrete and the longitudinal reinforcement is demonstrated in Figure 10. It is apparent from the figure that the increase in the aspect ratio decreases the strain for both concrete and reinforcement by a wide margin. This indicates higher lateral load capacity of both concrete and longitudinal reinforcement at higher aspect ratio of the bridge pier. But in case of developing the plastic hinge length, it varies only between 0.055h to 0.20h.

5.4 *Effect of Thickness of FRP*

This study included the effect of thicknesses of FRP as a parameter for finding the plastic hinge length in bridge pier. For this purpose, two thickness (1.5mm & 10mm) were chosen to simulate the numerical models. For both of the cases axial load, aspect ratio and longitudinal reinforcement ratio were kept constant. From Figure 11, it can be seen that with the increase in thickness of the surrounding FRP sheet the strain profile of core concrete and reinforcement smoothens out. A sudden change in strain profile is absent when the thickness is increased. Though the formation length of plastic hinge varies from 0.20h to 0.30h when thickness is increased from 1.5mm to 10mm. This kind of change in plastic hinge length indicates that higher confinement provided by the FRP sheet shifts the maximum damage location from the bottom to the middle of the bridge pier.

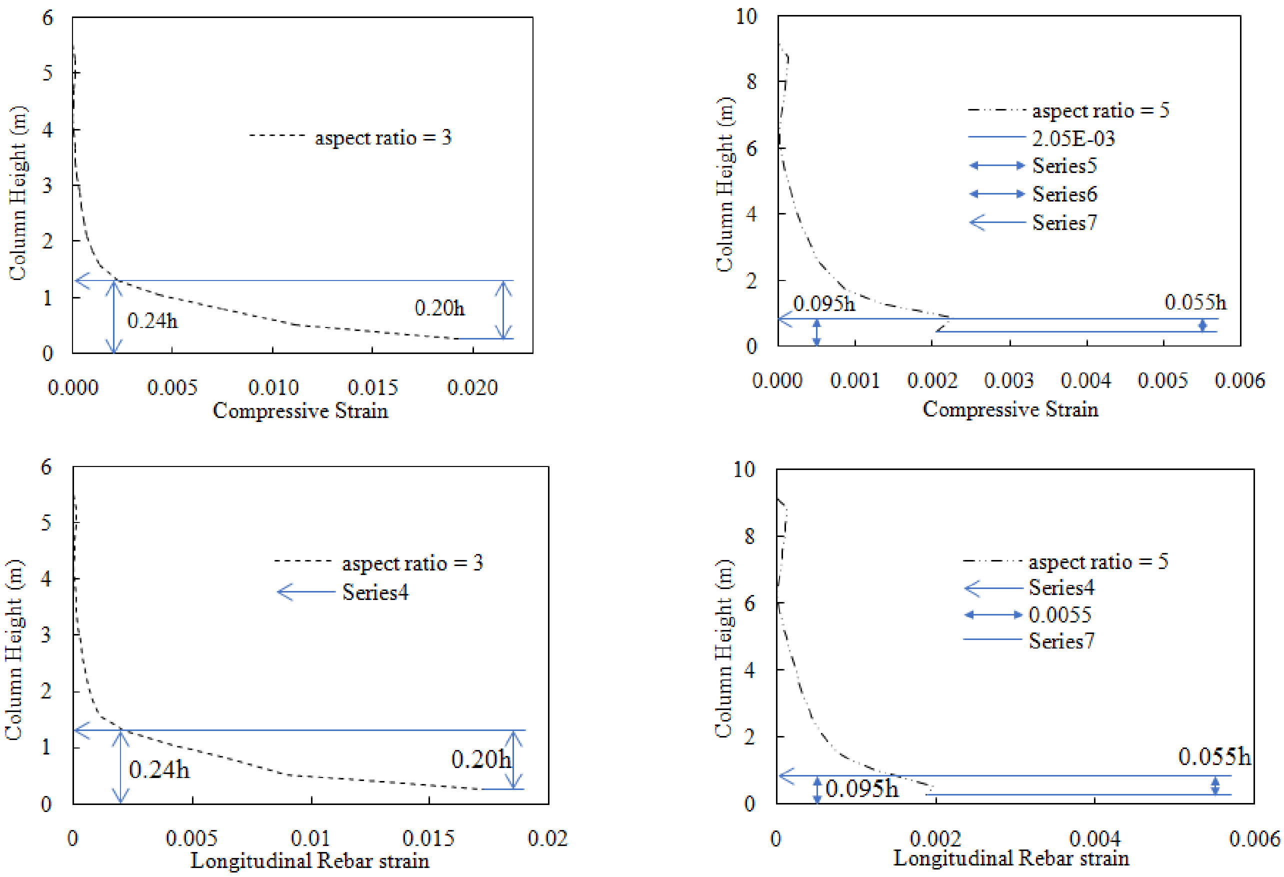

Figure 10. Effect of aspect ratio on core concrete and longitudinal rebar strain profiles.

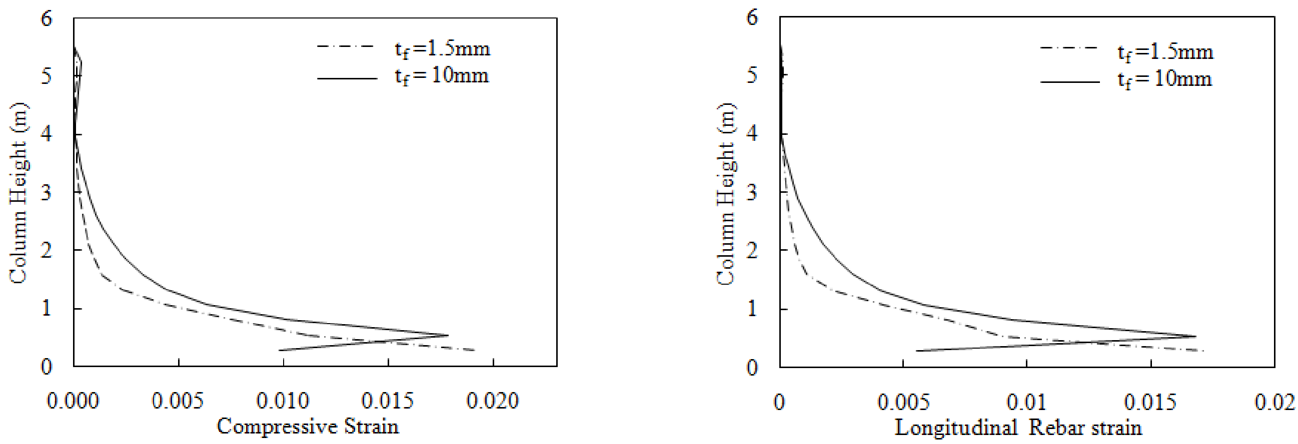

Figure 11. Effect of thickness of FRP on core concrete and longitudinal rebar strain profiles.

6 EXPRESSION FOR PLASTIC HINGE LENGTH

This study conducted on five different parameters to investigate the plastic hinge length of FRP wrapped RC bridge pier. The position of FRP wrap was not included in the expression as they require standalone expression of their own. Only fully wrapped pier with four different parameters were considered developing the expression. The analysis results demonstrated that the axial load, longitudinal reinforcement ratio, aspect ratio and thickness of FRP sheet has a great impact on formation of plastic hinge in a bridge pier. Based on the analysis results, linear relationship between these parameters (P/P_0, L/d, ρ_s and t_f) and plastic hinge length was developed through calibration. After conducting a series of least square analysis on the analytical result, equation 1 was generated.

$$\frac{l_p}{h} = \frac{1}{5}\left\{-\left(0.67 * \frac{P}{P_0}\right) - (3.9 * \rho_s) - \left(0.354 * \frac{L}{d}\right) + \left(0.061 * t_f\right) + 1.05\right\} + 0.205 \quad (1)$$

where, l_p is the plastic hinge length in mm, h is the total height of the pier. A comparison of plastic hinge length obtained from numerical analysis and Equation 1 is shown in Figure 12. At higher axial load levels, aspect ratio, reinforcement ratio and thickness of FRP, some level of discrepancies can be seen in the plastic hinge length obtained from the analysis and Equation 1. As the analytically obtained plastic hinge lengths are approximated values, overestimated values from Equation 1 can be considered as a conservative approach to get the plastic hinge length and deformation capacity of concrete columns.

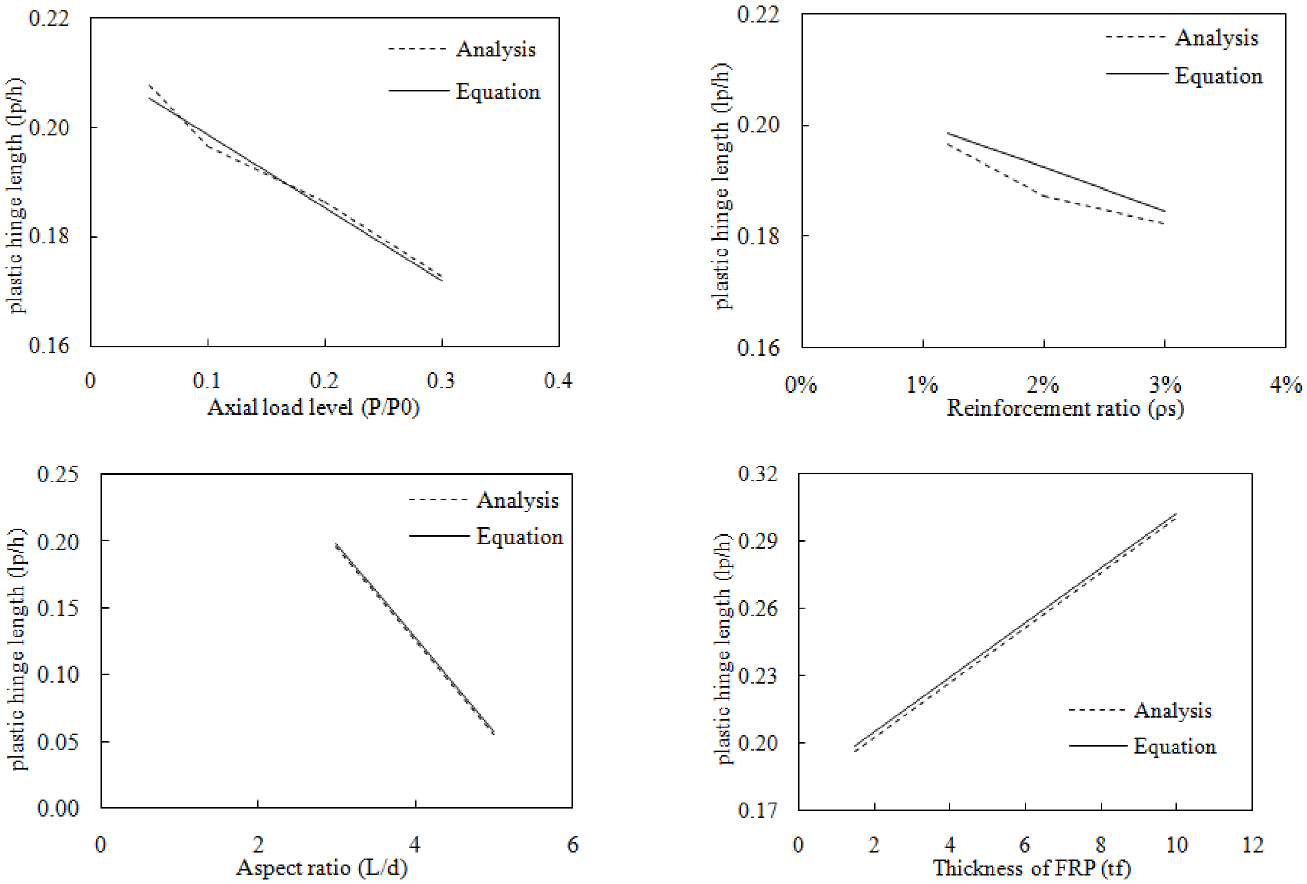

Figure 12. Plastic hinge length: equation versus analysis.

7 CONCLUSIONS

The key aim of this study was to develop a simplified equation using an empirical method that can be used to evaluate the plastic hinge length of a concrete bridge pier wrapped with fiber reinforced polymer (FRP). As a consequence, a plastic hinge length expression was introduced considering the influence of the axial load level, the longitudinal reinforcement ratio, the aspect ratio and the thickness of the FRP bridge pier. The following hypotheses can be taken from the research:

- This study found that the plastic hinge length decreases with the increase in axial load, reinforcement ratio and aspect ratio of the bridge pier; but increases when the thickness of the FRP sheet is increased.
- Different positions of FRP confinement produces the plastic hinge at different locations.
- The expression proposed in this study estimates the plastic hinge length quite accurately.

In this research, the proposed expression provides the length of the plastic hinge, taking into consideration both the core concrete and the longitudinal reinforcement of the bridge pier strain profile. Further research is needed in order to achieve more precision in predicting the length of the plastic hinge. More parameters should be regarded and controllable experiments can be performed to accurately measure the length of the plastic hinge.

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