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INELASTIC MODELING OF RC STRUCTURAL WALLS

M. Elnady [1] and Ahmed Ghobarah [2]

ABSTRACT

The principal objective of this study is to analytically evaluate the seismic behaviour of reinforced concrete (RC) structural walls. This objective was achieved through experimental and analytical investigations. The analytical study involved evaluation of the inelastic dynamic response of RC nonductile structural walls as well as retrofitted walls. An efficient macroscopic model to represent the behaviour of RC structural walls when subjected to pushover, cyclic and dynamic seismic loads was developed. The proposed model was intended to adequately describe the hysteretic behaviour of walls and to be capable of accurately predicting both flexural and shear components of inelastic deformation. The model predictions were compared with the experimental results. The comparisons showed that the developed analytical model predicted the inelastic walls response with a good accuracy. The analytical model was capable of representing the nonlinear dynamic behaviour of RC structural walls under seismic excitation.

Introduction

The use of micro models and finite element models for seismic analysis of a multistory reinforced concrete structure is a time-consuming and complex task, (Ghobarah and Youssef 1999). On the other hand, macro modeling that permits efficient seismic analysis of the multistory RC structural wall is simpler and justified modeling scheme. Therefore, programs such as IDARC2D (Valles et al. 1996), DRAIN-2DX (Prakash and Powell 1993), and OpenSees (Mazzoni et al. 2007), have been used widely for the seismic analysis of structures especially for research purposes. The main advantages of these programs are their simplicity, speed of analysis and the capability to model and analyze a large structure. The proposed macroscopic model is intended to adequately describe the hysteretic behaviour of reinforced concrete wall elements and to be capable of accurately predicting both flexural and shear components of inelastic deformation. The approach to develop the analytical model was verified by comparing the model results with the experimental results. Cyclic tests result included the hysteretic moment-rotation, shear force-shear deformation, and shear force-lateral displacement relationships. Using cyclic loading test results as a verification of the input to the model parameters ensures that the earthquake dynamic loads are simulated by the analysis. To analytically reproduce the response of the tested walls', a model of RC structural

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[1] Assistant professor, Dept. of Structural Engineering, Mansoura University, Mansoura, Egypt, 35516
[2] Professor, Dept. of Civil Engineering, McMaster University, Hamilton, ON, Canada, L8S 4L7

walls was developed and implemented into OpenSees nonlinear analysis software. OpenSees analysis software was selected because it incorporates a large and reliable library of nonlinear material models, which is suitable for fast and simple yet accurate analysis of RC structural walls. OpenSees program incorporates hysteretic models controlled by parameters that model the stiffness degradation, strength deterioration, and pinching of the hysteretic loops.

Material Models

The hysteretic rules defining the cyclic force-displacement curves of concrete and reinforcement steel are described in the following sections. Strength degradation and concrete model strength softening due to concrete crushing as well as steel model strength softening due to bond slip failure were considered.

Concrete models

The relationship between the force and the deformation (displacement) of the spring representing the concrete constitutes the concrete model. The concrete may be subjected to compression or tension stresses. In this study, the concrete compression envelope proposed by (Popovics 1973) for unconfined concrete elements and modified by (Mander et al. 1988) for steel-confined concrete elements were adopted. Model of carbon fibre reinforced polymers (CFRP) sheets-confined reinforced concrete walls was included in this study.

Concrete Tension Envelope

A linear stress-strain relationship was assumed for concrete in tension until cracking. The element response after cracking depends on the reinforcement ratio in the section. For an unreinforced member, the concrete tensile strength rapidly reduces to zero. The average remaining tensile stress transferred to the concrete after cracking of a member is a function of the bond characteristics between the concrete and steel. This remaining tensile strength is known as tension stiffening. Figure 1 shows concrete tension envelope in which α_t is a factor that defines the residual concrete tensile strength f_{ct} and f_{cr} is the concrete cracking strength.

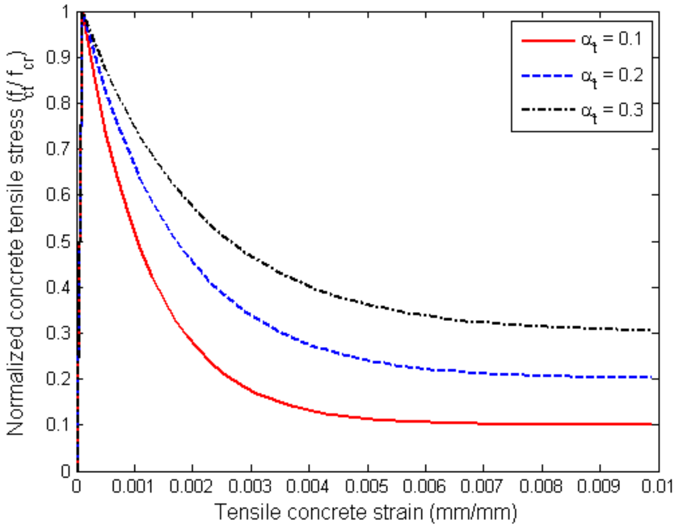


Figure 1. Concrete tension envelope (Stevens et al., 1987)

Envelope of concrete compression confined with steel ties

The response of concrete elements changes significantly under confining lateral pressure. The confining pressure is created because of the lateral dilation of concrete section. For steel-confined concrete, the confining pressure increases until a constant confining pressure, which corresponds to the yield stress of the steel ties, is developed (Mander et al. 1988).

Envelope of concrete compression confined with FRP sheets

Fibre reinforced polymer (FRP) confinement applies an increasing confining pressure up to failure. This is due to the elastic behaviour of the FRP materials. Therefore, the interaction between the FRP confinement and the concrete section need to be considered until failure of wrapping.

Most of the available analytical models focused on circular concrete sections, rather than square or rectangular sections (Samaan et al. 1998; Spoelstra and Monti 1999; Fam and Rizkalla 2001; Assa et al. 2001; and Wang and Restrepo 2001). El-Amoury (2004) proposed a model to predict the response of rectangular concrete sections confined with CFRP sheets and subjected to a monotonic axial compressive stress for concrete joints panels. El-Amoury used Mander et al. model for steel confined concrete to represent the FRP confinement in a manner similar to the steel ties. The confinement analysis for walls needs to be developed due to the lack of available models. Since they are the most stressed parts of the wall, end zone columns need adequate confinement. For end zone confined concrete with steel ties, the same model of Mander et al. (1988) for confined concrete by assuming constant confinement pressure, can be used.

Composite CFRP jacket applies confinement lateral pressure by arching action at the corner of rectangular section. Chamfering edges to an appropriate diameter is necessary for better distribution of the compression stresses and for minimizing the stress concentration in the FRP jacket. An appropriate choice of the arching angle must to be made to calculate the effective confined section. Mander et al. (1988) assumed an arching angle value of 45° for steel-confined concrete sections. Wang and Restrepo, (2001) reported that a suitable arching angle for CFRP-confined sections varies between 42° and 47°; depending on the number of plies and they suggested that an average value of 45° for the arching angle. In this study, the concentrated corner confining pressure was distributed as uniform lateral pressure along the end zone sides. The end zone dimensions were assumed equal to the area enclosed by the U shaped CFRP jacket and the steel anchors.

The evaluation of Poisson's ratio is a challenge for using this technique because it varies with the levels of imposed axial strain and the corresponding confinement pressure. Several researchers attempted to make realistic prediction of this ratio. For example, Wang and Restrepo (2001) reported a constant average Poisson’s ratio for evaluating the confinement pressure. Fam and Rizkalla (2001) employed simple regression analysis to predict Poisson's ratio at different constant confining hydrostatic pressure. An empirical formula was suggested by Spoelstra and Monti (1999) to evaluate the lateral concrete deformation. A conservative estimate of Poisson's ratio was made for the purpose of this study. Poisson's ratio of 0.50 was used to cover most of axial strain values as suggested by Wang and Restrepo (2001). The effectiveness of the FRP confinement jacket was considered by a confinement efficiency factor. Figure 2 shows the stress-strain relationships for unconfined, steel ties confined, and CFRP confined concrete with the unconfined concrete strength from concrete cylinder compression tests, f_c' of 38 MPa.

Reinforcement steel model

The steel model refers to the relationship between the force and deformation in the steel bars. The bar extension and bar anchorage-slip of an embedded bar in concrete element are the main sources of steel spring inelasticity as well as the bond law between the steel rebar and concrete. Several researchers investigated the bond-slip behaviour of steel bars embedded in concrete experimentally (Marques and Jirsa 1975; Viwathanatepa et al. 1979; Soroushian et al. 1988; Soroushian and Choi 1989; Soroushian et al. 1991a). In addition, several analytical models were developed to predict the bond stress-slip relationship of steel bars embedded in concrete (Ciampi et al. 1982; Filippou et al. 1983; Soroushian and Choi 1991; Soroushian et al. 1991b; Alsiwat and Saatcioglu 1992; Monti et al. 1997; Youssef 2000; Galal 2002, El-Amoury 2004; and Khalil 2005). The model developed by Alsiwat and Saatcioglu, (1992) was used to establish the monotonic envelope between force-deformation of steel bars embedded in concrete. This model results correlates well with experimental results (Galal 2002, El-Amoury 2004; and Khalil 2005). Because of its simplicity and reasonable accuracy, El-Amoury, 2004 model is used in this study to plot the monotonic response of embedded steel bars. El-Amoury model is the same as Alsiwat and Saatcioglu, (1992) model but with minor refinements. A bilinear steel constitutive relationship with two slopes was assumed for steel bar anchored in concrete element. The first slope is up to the onset of yield strain and the second slope starts from yielding of the steel to the ultimate strength.

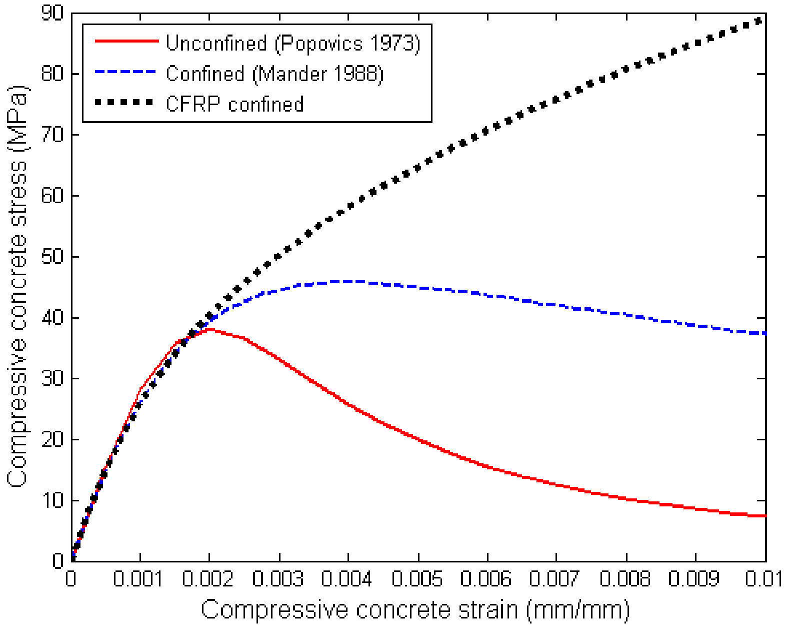


Figure 2. Stress-strain behaviour of unconfined and steel confined concrete members

Structural Wall Shear Model

Several components contribute to the reinforced concrete structural walls shear load resistance. In the elastic range, the concrete can provide a considerable contribution to the lateral load resistance. The concrete contribution deteriorates with crack development and cyclic lateral load reversals. Therefore, the transverse reinforcement is essential to prevent brittle shear failure.

Walls with external CFRP shear reinforcement have the additional shear resistance contribution of the FRP. These three shear resistance components behave in different manners under the same loading for the same structural element. For example, FRP behaves linearly up to failure. On other hand, the concrete shows a nonlinear response up to ultimate strain and its strength deteriorates after peak stress in several different ways according to the confinement level. The shear reinforcement behaves linearly up to yield and can be assumed to have isotropic strain hardening after that. These three materials contribute simultaneously to the lateral load resistance mechanism. For cases where an access to a large number of experimental hysteretic envelope curves is limited, the modified compression field theory (MCFT) can be used to define the envelope curve for the hysteretic material model of the shear behviour, (Vecchio and Collins 1986). Several researchers (Yousef 2000; Galal 2002; El-Almoury 2004; and Khalil 2005) reported that the MCFT prediction of the shear behaviour of the structural concrete elements can provide a good accuracy when compared experimental data that was available.

Modeling of CFRP-Shear Strength Contribution

When modeling RC structural wall strengthened with FRP composites, the effect of the composite jacket with anchored ends can be idealized as distributed ties in the RC wall. The response of concrete wall with externally bonded FRP composites was evaluated using MCFT. The problem is represented by three sets of equations. They are the constitutive laws, compatibility conditions and equilibrium conditions as reported elsewhere (Elnady 2008).

Solution strategy

Iterations are carried out over an incrementally increasing shear strain, γ. For each iteration a value of γ was imposed, axial strains were assumed, then principal strains and stresses were estimated. The shear force was calculated and the axial force was estimated and until equilibrium was achieved. The process was repeated by imposed another shear strain increment.

Analysis Options

Element material properties from test data

Two options for defining the material properties for each element were available. Either the analysis program generates the envelopes for the elements based on concrete and reinforcement materials properties, or the program is provided with complete moment-curvature envelope data from tests. If access to experimental envelopes is not available, it is possible to use other programs to generate the envelopes of the moment-curvature and shear force-shear deformation. In this analysis, the first option was used to generate the moment-curvature and shear force-shear deformation envelopes for each wall element. In order to check the accuracy of the program predictions, its results were compared with the available experimental envelopes and a good agreement was observed. This ensures that the effects of reduced stiffness are included in the analysis. By using the first option, (i.e. providing the material properties for program to generate envelopes), and taking into account the stiffness degradation of the reinforced concrete members, it can result reliable and accurate analytical model results in the case of seismic loading.

Hysteretic rules

The hysteretic values should characterize stiffness degradation, strength deterioration, and pinching behaviour for the RC structural walls. For simulation of the experimental results, the values were obtained by a trial and error procedure. Therefore, after determination of the element properties for RC structural walls, several analyses were carried out with different values of hysteretic parameters and those that yielded the most comparable results to the experiments were selected to be implemented in the simulation of the tested walls. Ductile walls have small values of stiffness degradation, strength deterioration and bond slip. The rehabilitated walls have large volumes of well-anchored longitudinal reinforcement and the CFRP shear strengthening helped to fully mobilize the mechanism of the shear resistance of the walls. For modeling the inelastic behaviour of the tested walls, a model which takes into account stiffness degradation parameter, strength deterioration parameter, and slip-lock parameter was used.

Hysteretic model

The above solution strategy establishes the envelope curve for the shear elements. Every point on this curve was evaluated for the corresponding axial force acting on the structural wall represented by the shear element. The modified compression field theory has the ability of determining the point at which degradation in shear strength will start and thus modelling of failure is included in the shear element. To account for the continually varying stiffness and energy absorption characteristics under cyclic loading, suitable hysteretic rules are needed. Hysteretic rules are discussed in the previous section. The proposed wall model is shown in Figs. 3 and 4. The model employs the fiber section technique for modeling flexural response along with a hysteretic shear model. Distinction was made between unconfined, steel confined, and CFRP confined concrete areas in the concrete modeling. The hysteretic shear model incorporated important features such as stiffness degradation, strength deterioration, and pinching effects. In a typical reversed shear cycle, as loading is increased, a significant reduction in the tangent stiffness occurs which represents the pinching effect experienced by RC structures under cyclic loading. The proposed model is characterized by its simplicity and its ability to describe the pinching experienced because of shear deformations under cyclic loading by using simple loading and unloading rules. The envelopes of the moment-curvature were generated using sectional analysis.

Analysis type

The objective of the modeling is to reproduce the behaviour of the tested walls using a simple and accurate analytical modeling. The tests were conducted using cyclic displacement histories under displacement control of three synchronized actuators (Elnady 2008). The same displacement histories, imposed on the tested walls during tests, were used as an input to the simulation analysis. The solution was performed incrementally assuming the properties of the structure such as the flexural stiffness do not change during the time step. The analysis uses the pseudo time to perform the cyclic analysis under displacement control with user input time step. Analysis step size 0.01 mm was enough to balance between the time needed for the analysis and the accuracy of the results compared to the experimental results.

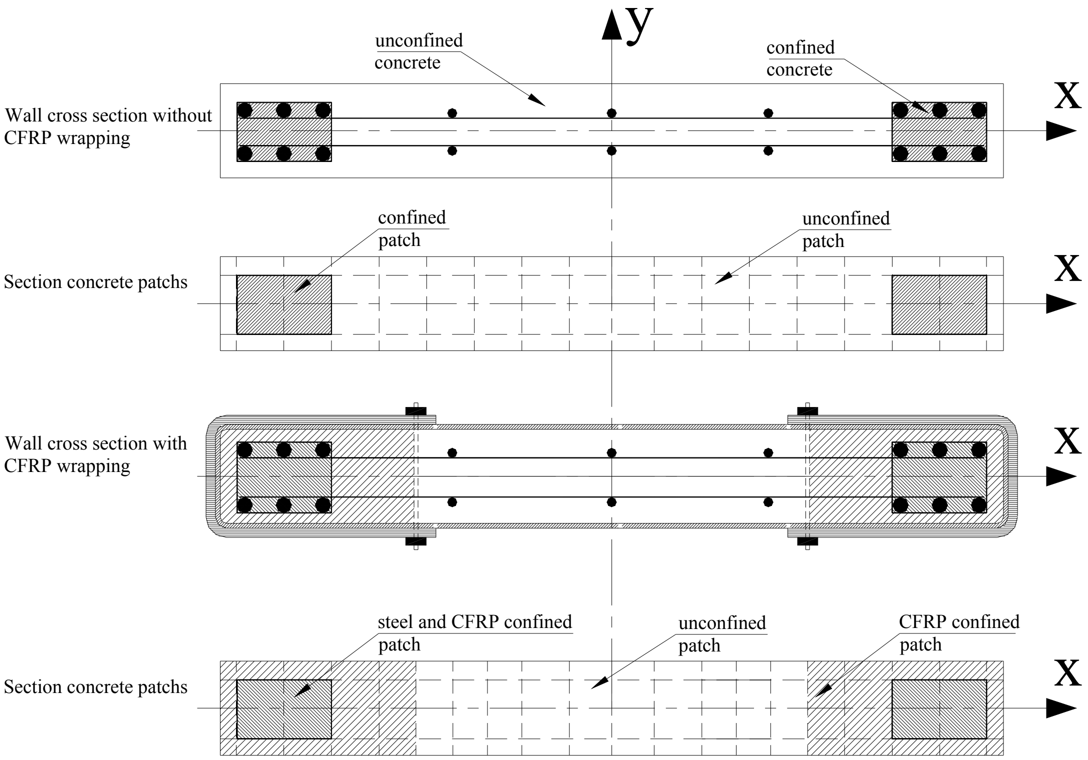
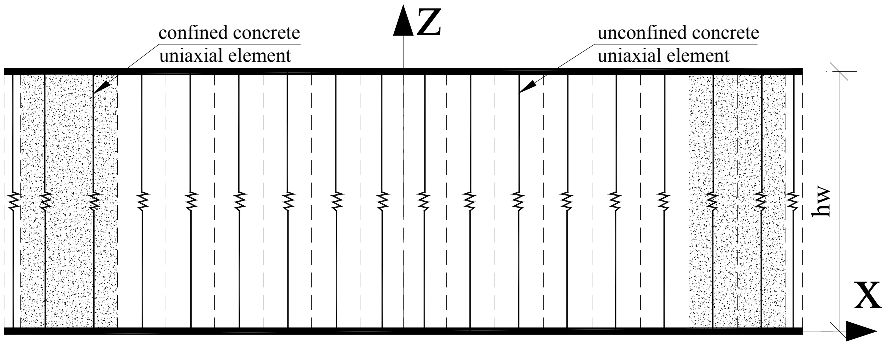
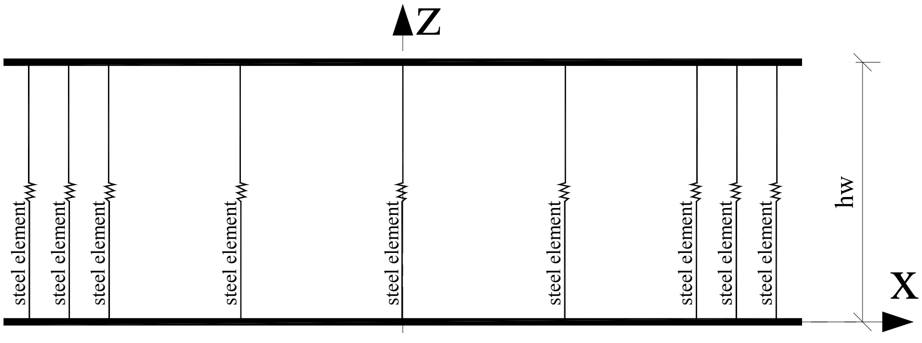


Figure 3. Proposed wall model section meshing



Uniaxial concrete elements



Uniaxial steel elements

Figure 4. Proposed wall model: steel and concrete elements

Results and Conclusions

The validation and accuracy of the developed model was established by using the model to reproduce the hysteretic behaviour of the tested walls. The validation of the hysteretic rule parameters controlling the behaviour of the tested walls has been achieved by reproducing the experimental results, with 10 % variation from the experimental results, of the tests using OpenSees analysis program. Good agreements were obtained from the analyses of the tested walls using both programs. Figure 5 shows the comparisons between the predicted and recorded test results. The comparisons show that the model implemented in OpenSees program predicted the response with a good accuracy. Observations from analysis results indicated that the stiffness degradation, strength deterioration and pinching behaviours were accurately simulated using the developed model.

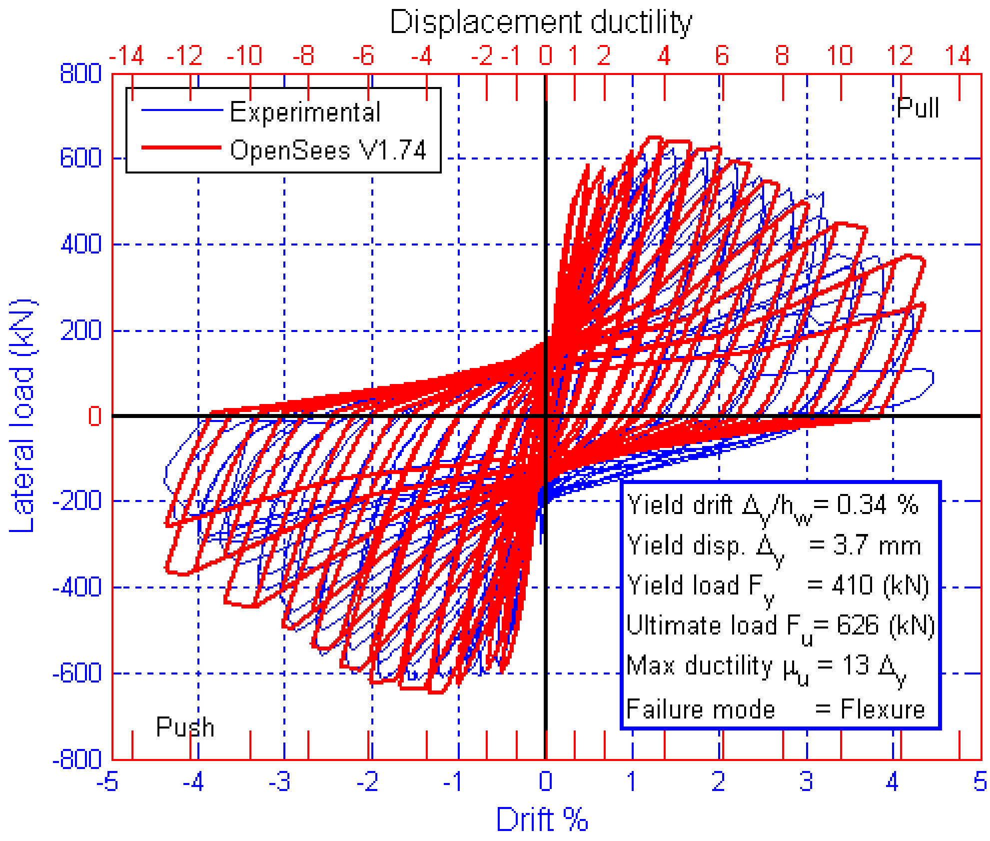


Figure 5. Wall RW7 top drift ratio- lateral load relationship

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