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Behavior of pre-stressed concrete bridge girders due to time dependent and temperature effects

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ABSTRACT: The service behaviors of pre-stressed concrete bridges are significantly affected due to time dependent effects like, Creep, Shrinkage and ambient Temperature. These are complex phenomena and are mainly influenced by characteristics of concrete, its exposure condition, humidity of air and stages of construction, which are sequential for pre-stressed concrete structures. These time dependent effects induce additional internal forces and causes deflection to the bridge superstructure which reduces the serviceability, durability & stability of the bridge in long run. This paper is prepared based on the field data's collected from two PSC box girder bridges to present the effects caused in the real structure due to development of strain on account of creep, shrinkage and atmospheric temperature. The trends of strain development in the bridge superstructure, as per field values are compared with the predicted values from two commonly used Model codes, ACI209R-92 and CEB-FIP 90. The paper also presents the effects, caused due to thermal stresses on account of daily variation in ambient temperature in two PSC box girders for two different boundary/end conditions. To access the quantum of damages that occurs in PSC bridge girders, due to these effects, the bridges of two different ages were considered. The vertical deflection of pre-stressed concrete girders due to loss in pre-stress is a natural phenomenon. In addition to this, it is observed that due to Creep, Shrinkage and daily atmospheric temperature variation in structural concrete there is a long-term deflection in Pre-stressed concrete girders. These causes decrease in service life of bridge and in long run it required strengthening with external pre-stressing to secure its original load bearing capacity.

Keywords: creep, shrinkage, pre-stressed concrete, thermal stress, box girder bridge,

Introduction:

Creep and Shrinkage have a considerable impact upon the performance of concrete structures, causing increased deflections as well as affecting stress distribution. The variation of creep and shrinkage properties in concrete is effected by various factors commonly classified as internal and external factors, from Bazant (1985). The change of environmental conditions, such as humidity & temperature may be considered as an external factor. The variation in quality and mix composition of the materials used in the concrete may be considered as internal factors. The effects of creep, shrinkage and atmospheric temperature variations in the structures like long span bridge girders may leads to excessive deformation and widespread cracks. They also affect the sizing and setting of expansion joints due to axial shortening arising from creep and shrinkage effects along with existence of prestressing force. Both creep & shrinkage may occur concurrently and reduce the pre-stressing forces in PSC bridge girders. Thus the time dependent effects may create havoc in the serviceability, durability and stability of bridge structure.

The time-dependent effects of concrete structures due to creep & shrinkage of concrete have not yet been controlled rationally despite great advances in theories & in design software. This fact results from the complexity of time dependent effects of concrete structures. Study on the various individual time effects due to creep and shrinkage in concrete structures can be found in the work of Gilbert (1988). The study conducted by Robertson (2005) in actual bridges for time dependent deflection shows that the difference between the calculated prediction and actual deflection in the bridge is large. This difference is due to inaccurate evaluation of pre-stressing force and thermal stress due to atmospheric temperature. From the report of Zollman CC (1985) & Massicotte B (1994), it is found that when prestress losses have become excessive, additional prestressing force has to be applied to the bridge during the service stage at a great cost to maintain the serviceability. Studies of Saiidi M (1996) (1998) on the time dependent prestress loss in actual post-tensioned concrete bridges shows that the difference between the calculated prediction and the actual prestress force is large.

Therefore purpose of this study is to present the type of strain development and deflection caused in PSC bridge superstructures due to time dependent effects. Analyzing field data’s for development of creep and shrinkage strain and compare with the predicted values from two Model codes, ACI209R-92 and CEB-FIP 90. The study also presents the development of strain and deflection in PSC girders due to daily variation in ambient temperature. The paper highlighted the condition of a balanced cantilever PSC box girder bridge only after fifteen year of services.

2.1 Time dependent effects in concrete structures:

2.1.1 Creep:

Creep phenomenon may be defined as the property of concrete by which it continues to deform with time under sustained loads at unit stresses within the acceptable elastic range (i.e below 0.5 f'_c). It is obtained by subtracting from the total measured strain in a loaded specimen, the sum of the initial instantaneous (in elastic range) strain due to the sustained stress, the shrinkage, and the eventual thermal strain in an identical load-free specimen which is subjected to the same history of relative humidity and temperature conditions. Conveniently creep may be designated at constant stress under condition of steady relative humidity and temperature, assuming strain at loading as the instantaneous strain at any time. The definition of creep lumps together the basic creep and the drying creep.

a) Basic creep occurs under condition of no moisture movement to or from the environment.
b) Drying creep occurs as an additional creep due to drying.

2.1.2 Shrinkage:

Shrinkage is the property of concrete to change in volume independent of the load it sustains. It is essentially due to evaporation of water from concrete and hydration of its components with time, which occurs without any external stress to the concrete. Shrinkage is usually expressed as a dimensionless strain under steady condition of relative humidity and temperature. There are mainly three phenomena causing total shrinkage of concrete: drying shrinkage, autogenous shrinkage and carbonation shrinkage.

a) Drying shrinkage is due to loss of moisture in the concrete.
b) Autogenous shrinkage is due to hydration of cement.
c) Carbonation shrinkage is due to carbonation of various cement hydration product in presence of CO.

2.1.3 Thermal Stress:

Generally concrete bridge structures are subjected to thermal effects due to the interaction with air temperature and solar radiation, leads to seasonal and daily temperature changes in the structure. The seasonal variation corresponds to the maximum mean temperature change expected to occur during the year. Due to the poor thermal conductivity of concrete, the temperature also changes hourly from the surface to the interior points of the structure and causes daily nonlinear temperature distribution across the section. As a result thermal stress will always be present within the section along the depth of the girder section. These stress variation causes development of strain variation and also deflection in the bridge girder section. Solution of the heat flow equation for different ambient conditions supported by the experimental results obtained by Emanuel and Lewis (1981) and defined critical design temperature gradients. In the past decades extensive studies have been conducted regarding temperature effects on concrete bridges (1981) (2009) (1978). The nonlinear temperature distribution that arises in concrete structures in the early days, after concreting, lead to tensile stress which may also causes cracking of young concrete.

3.1 Uncertainty Modeling of Shrinkage & Creep of concrete:

Over the years, parameters that influence creep and shrinkage of concrete were established, even though these phenomena cannot be separated from each other. These parameters allow for predicting the creep and shrinkage phenomenon and therefore the behaviour of a structure. The parameters included the water cement ratio, the curing method, the ambient humidity, the aggregates, air content and the age at loading. Several material models for shrinkage and creep of concrete have been proposed both in literature and in design codes. The commonly used models in the codes are those suggested by the ACI Committee 209R-92 (1992) and the CEB-FIP MC (1990). These two model codes are based on extensive research as well as experimental studies.

In 1992 the American Concrete Institute (ACI) recommends the procedure for the prediction of creep, shrinkage and temperature effects in concrete structure in its ACI-209R-92 codal provisions. It presents the designer with a unified and designated approach to the problem of volume change in concrete. This procedure is applicable for normal weight and all the light weight concrete, using both moist and steam curing and Type I and III cement under the standard conditions as shown in Table-1. Correction factors are used for the conditions other than the standards.

In 1990, the Comite Europeen du Beton (CEB) adopted new guidelines for prediction of creep and shrinkage for structural concretes, having 28 days mean cylindrical compressive strength varying from 12 to 80 Mpa, mean relative humidity 40-100% and mean temperature 5-30ºC.

4.1 Comparison of predicted values from Model Codes for Shrinkage Strain & Creep compliance & collected field data's :

Arolli Bridge over Thane Creek in Navi Mumbai, India is 1030 meter long with 2 carriageways of 3 lanes in each direction. It consists of 42 PSC single cell box girders of 50 meter length (c/c of pier). The width of deck slab is 14.98 meter for each carriageway. Each main span girder is made up of precast pre-stressed single cell box girder as shown in fig- 1 with inclined web of constant 3.2 meter depth. Each box girder is supported on 4 PTFE bearings fixed on pedestals over the pier caps.

The values of creep coefficient and shrinkage strain based on the prediction models ACI 209R-92 and CEB-FIP 90 for the box girder, with respect to time is calculated by developing a computer program. The shrinkage strain and creep compliance values as obtained are plotted against age of concrete as shown in Fig- 2 & 3 respectively. Similar values are also obtained using Bridge designing software 'Midas Civil' for creep coefficient and shrinkage strain.

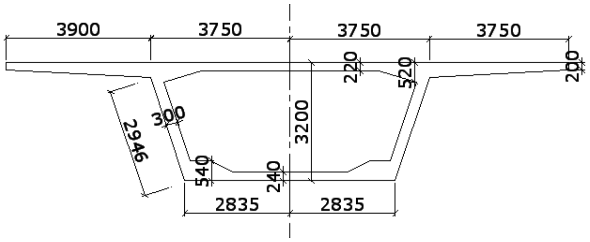

Fig: 1 Cross section of single cell precast pre-stressed box girder

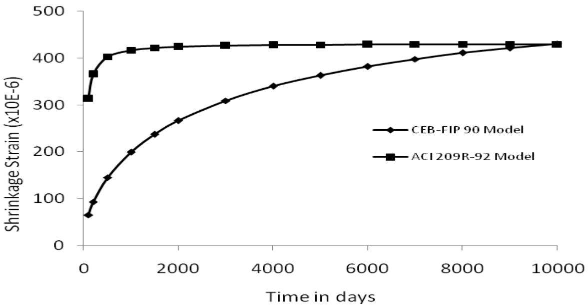

Fig: 2 Prediction of Shrinkage strain using Model Codes

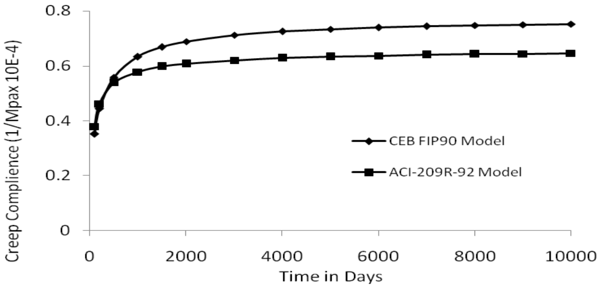

Fig: 3 Prediction of Creep Compliance using Model codes.

From the fig- 2 it is observed that predicted values for shrinkage strain using ACI 209R-92 model code are larger than that using CEB-FIP 90 model code, at early age of concrete but at latter age of concrete the shrinkage strain from both the model codes are almost equal.

From fig- 3 it is observed that predicted values for creep compliance using ACI 209R-92 model code are smaller than that using CEB-FIP 90 model code, at early age of concrete, but with the age of concrete the difference between the values increases.

As per ACI 209R-92, the increase in creep after, say 100 to 200 days of concreting is usually more pronounced than shrinkage. The shrinkage usually increases more rapidly in percent of ultimate value, during first few weeks of concreting. The similar prediction was also observed in the work of In-Hwan Yang, (2003) for probabilistic analysis of creep and shrinkage effects in PSC box girder bridges.

Vibrating Wire strain gauges having sensitivity of ± 1 με were embedded at particular locations in soffit, web and deck slab of the PSC Box girder (fig-1) during concreting for collection of strain data’s from field. The development of strain was monitored and recorded for approximately 800 days from the day of concreting of box girder section. A graph as shown in fig-4 is plotted based on recorded field data’s for development of strain in soffit, web and deck slab of box girder with the age of concrete.

From the graph (fig-4) it can be observed, that the maximum strain due to combine effect of creep and shrinkage in soffit, web and deck slabs were in and around 350 days from the day of concreting of girder. After development of maximum strain, the strain value decreases with time and become more or less constant with age of concrete.

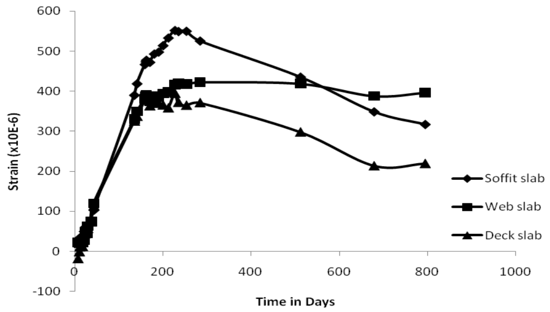

Fig- 4. Development of strain with time in concrete box girder section.

On comparison between predicted values (fig-2 & 3) and real field values (fig-4) it is observed that predicted values for shrinkage strain and creep compliance are maximum at age of concrete around 350 day and there after rate of increases of strain is very nominal with time. Whereas field values shows development of maximum strains in and around 350 days from the day of concreting and there after strain reduces before becoming almost constant. From the graphs it can also be observed that predicted values for shrinkage strain and creep compliance as per Model Code dose not show any sign of decrease with age of concrete after attaining maximum values.

5.1 Deflection of Simply Supported PSC box girder due to development of creep & shrinkage strain:

Creep and shrinkage causes continuous change in the stresses in concrete and steel in any reinforced or pre-stressed concrete members. The knowledge of this change in stress is of interest for a number of reasons. For instance, in pre-stressed concrete, we can determine the loss of pre-stress, and the time dependent deformations such as axial shortening and deflection, knowing the change in stress and the associate strains.

The deflection of the Arolli Bridge girder, G-7 along the span was recorded after application of final stage of pre-stressing and upto 390 days from the date of concreting. The effect of creep & shrinkage strain in development of deflection of girder with age of concrete is obtained on analyzing the recorded data. From the deflection pattern as shown in fig-5 it is observed that there is maximum deflection of 5.6 mm of hogging in nature, at mid span of the girder after 390 days of concreting. The deflection was measured using precession level upto accuracy of 0.1 mm in no traffic load condition.

For the same single cell PSC concrete box girder the development of maximum strain (fig-4) due to creep and shrinkage of concrete was observed in and around 350 days from the day of concreting. So the effect of shortening of concrete girder due to creep and shrinkage causes the deflection at mid span and due to presence of pre-stressing force throughout the girder length the deflection caused is hogging in nature.

Generally, bridge is subjected to the effects of weather changes both daily and seasonal. The phenomenon of development of temperature gradient, strain and deflection on account of such changes in ambient condition is complex. This thermal effect should be considered in the design process for serviceability limit state conditions, namely those associated with cracking of the structure or excessive displacements.

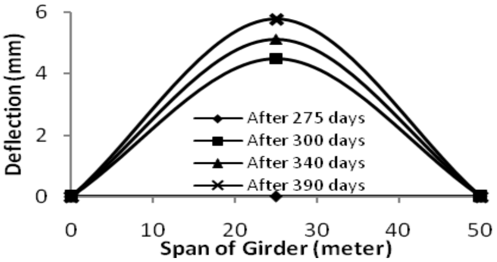

Fig-5: Deflection profile of pre-stressed concrete Box Girder.

6.1 Effects of ambient temperature on PSC box girders:

Temperature is the major environmental factors which also influence the effect of creep and shrinkage. The effect of change in temperature on concrete creep and shrinkage is basically two-fold. First, they directly influence the time ratio rate. Second, they also effect the rate of aging of the concrete, i.e the change of material properties due to progress of cement hydration.

The nonlinear temperature distribution T, in the cross section of bridge superstructures can be sub-divided in a uniform temperature T_m, in a linear gradient for each direction associated with a temperature difference ΔT and in a nonlinear distribution T_o as shown in fig.6.

The two components T_m and ΔT are associated with the longitudinal displacements and curvatures of the bridge girder. The movement of the structures associated with these two components, can be determined by linear elastic method for statically determinate structures. For statically indeterminate structures as movements are restrained, thermal forces arise, which are required to be considered in design.

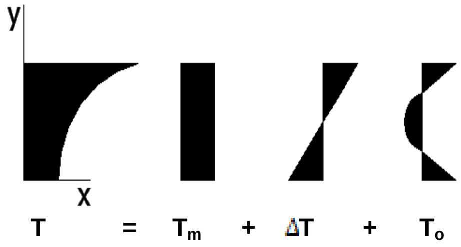

Fig: 6 Thermal stress components

6.1.1 Deflection and development of strain in Simply Supported PSC Box Girder due to atmospheric temperature.

The development of strain and deflections over the bridge girder, G-13 of Arolli Bridge were recorded throughout the day at different temperature in no traffic load condition to determine the effect of atmospheric temperature. The deflection pattern of this 50 meter length girder after 600 days of concreting is obtained on analyzing the recorded data. The cross section of the PSC box girder is shown in fig-1. Deflection measurements were carried out using high precision N3 level with an accuracy of 0.1mm. The deflection pattern of the box girder as obtained at different temperature of a day is shown in fig-7 & fig-8. Due to poor thermal conductivity of concrete, the temperature changes hourly from surface to the interior points of the bridge and daily nonlinear temperature distribution arises. Due to this temperature variation across the section and presence of pre-stressing force along the length of the girder there is development of deflection with increase in temperature which is hogging in nature.

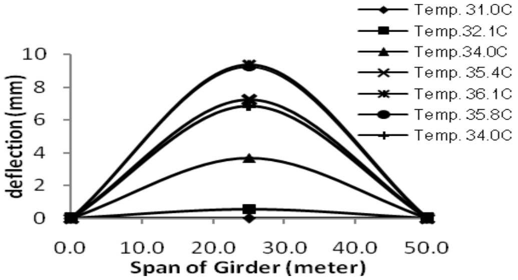

Fig: 7 Pattern of deflection of box girder G-13 at different temperature

The development of strains and temperatures were obtained, using vibrating wire strain gauges embedded at mid span of the girder on soffit and deck slab. Strain development due to temperature in soffit slab and deck slab of the box girder are shown in fig-9 & fig-10 respectively. From the plotted graph it can be clearly observed that, on account of temperature rise there is development of compression in soffit slab and tension in deck slab. Due to occurrence of this different nature of strain, in soffit (compression) & deck (tension) slab there is tendency of hogging effect in the pre-stressed concrete box girder. The deflection pattern is shown in fig-7 for the PSC simply supported box girder G-13. Plotting graph between temperature vs deflection as in fig-8, it is observed that with increase in 5ºC (31ºC to 36ºC) ambient temperature during day time, there is increases in deflection of girder by 9.5mm at mid span. The deflection of PSC Girder again reduces or come back to its original position on decreases of atmospheric temperature during night time. Daily repetition of same deflection pattern in PSC bridge girder may give rise to the formation of cracks and causes deterioration at latter age.

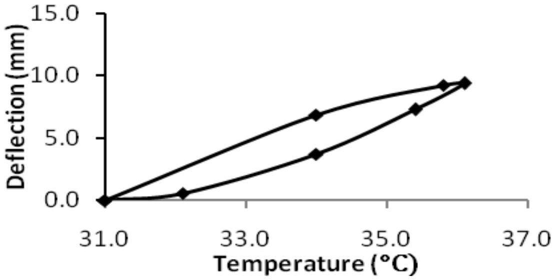

Fig: 8 Temperature vs Deflection of box girder G-13

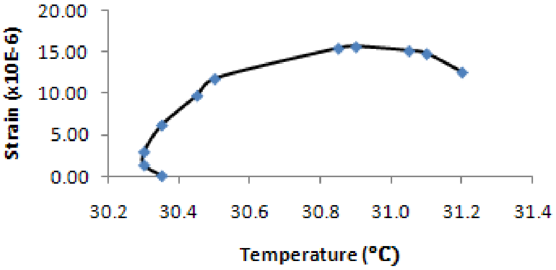

Fig: 9. Strain vs Temperature in Soffit slab of Box Girder bridge at mid span

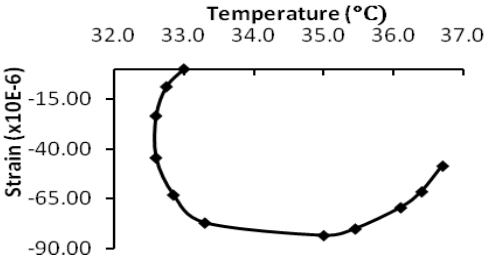

Fig: 10 Strain vs Temperature in Deck slab of Box Girder Bridge at mid span

6.1.2 Deflection of balanced cantilever PSC box girder due to atmospheric temperature:

The Zuari bridge at Goa, India is a balanced cantilever box girder bridge with its two arms spanning on both side of the abutment. The depth of box girder varies from 8.0 m. at the pier to 2.25 m. at the tip of the cantilever arms. The length of one cantilever arm is 58.40 m. and another is 58.66 m. which are connected to the next cantilever arm through hinges. The bridge is a single cell non-prismatic box girder having a two lane carriageway and footpath on either side. Fig-11 shows the general arrangement of the cantilever bridge girder over pier P-4. This typical case study was taken up to access the behavior of PSC balanced cantilever box girder bridge after 15 year of service.

The behavior of the bridge in terms of deflection during day time at different atmospheric temperature was recorded in no traffic load condition. High precision N3 level with an accuracy of 0.1mm directly, was used for deflection measurements. The deflection of cantilever arms at different atmospheric temperature is plotted in fig.-12.

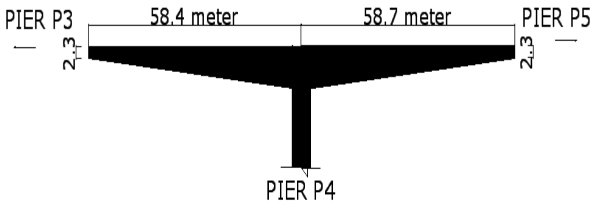

Fig: 11. Elevation of pre-stressed balanced cantilever box girder P-4

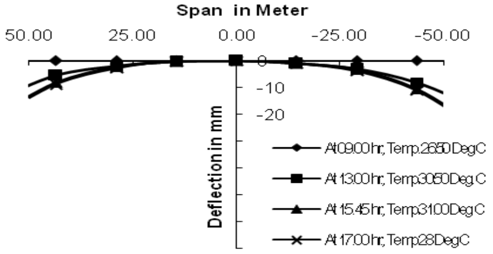

Fig:12 Deflection profile of balanced cantilever PSC bridge Girder.

From the graph it is observed that the tip of cantilevers shows downward deflection of average 24.5mm at maximum ambient temperature 31.0 °C. Plotting graph between temperature vs. deflection as shown in fig-13, it is observed that, with rise in temperature of only 4.5 ºC, (26.5ºC to 31.0ºC) during day time there is increase in downward deflection of 24.5 mm at the tip of PSC cantilever arms. During night hours when ambient temperature reduces, the deflection also reduces and PSC cantilever arms returns to its original position. The serviceability of the bridge has been reduced only after 15 year of construction and required to be strengthen with external pre-stressing.

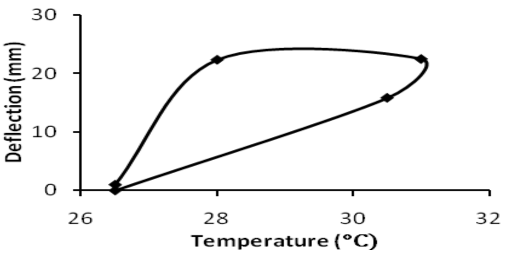

Fig:13, Temp. vs Deflection of PSC cantilever Girder

8.1 Conclusion:

Due to Creep & Shrinkage there is change in rheological and material properties of concrete with time which causes development of strain in prestressed concrete bridge superstructures. Other factor which also causes development of strain in PSC bridge superstructure is the nonlinear temperature distribution arises due to daily and seasonal variation of ambient temperature. In PSC bridge superstructure the developments of these strains are caused without any external load and depend only on time or age of concrete. The growth of strain due to creep and shrinkage is found to be almost constant after certain age of concrete which causes continuous deformation to the structure. If the prestressed concrete bridge girder is at hogging or sagging condition after application of final stage of pre-stress, the development of creep and shrinkage strain in the girder further increases the corresponding effect. In other word we can say, the development of time dependent strain in pre-stressed concrete bridge girders depends upon its state of deformation and stress at the time of applying load.

Development of strain in pre-stressed concrete bridges, due to daily atmospheric temperature variation is also significant. The daily development of strain and corresponding deflection of bridge girders may causes cracking of structure. Steel bars in the bridge structure may get corroded if they are exposed to moisture due to formation of thermal cracks. So, due to development of time dependent and thermal strains and corresponding deflections in PSC bridge superstructure, the service life is reduced in long run.

Hence it is very important to develop a smart system for concrete bridge structures, which can automatically adjust structural characteristics in response to external disturbances or unexpected service loading towards structural safety and increase life of bridge and its serviceability. Extensive research works are required to develop smart concrete structures, replacing a percentage of conventional steel reinforcement (Fe-415/500) with superelastic alloy. Laboratory scale experiments are required to be undertaken using superelastic alloys to overcome this time dependent & atmospheric temperature effects in concrete beams to enhance the service life of concrete structures.

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