Analysis and Design of Continuous Prestressed Concrete Bridge based on Construction Sequence

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Abstract. Continuous prestressed bridge are often analysed and designed using the final product of construction without considering their construction stages. This study explores the process of analysis and design of continuous prestressed concrete bridge based on construction stages on site. In this study, the construction sequence is first studied and understood. Several analysis of loadings acted on continuous bridge is conducted using Staad Pro software to determine the bending moment of the bridge at various construction sequence. Then, the bending moments obtained from the Staad Pro is used to design the cable profile, prestress force and number of tendons of the continuous bridge. The bending moment value due to selfweight obtained from the first construction stages are higher than last construction stages thus it is used to design the prestress force and number of tendons required by the continuous bridge on the stage of transfer while the combination of bending moment due to selfweight obtained from the first construction and bending moment due to external loading gained from the last construction stages are used to design the prestress force and number of tendons required on the stage of service respectively. Analysis of construction sequence is important during the designing process as the value of bending moment on the first construction stages are more critical compared to the last construction stages.

Introduction

Prestressed concrete are often chosen by developer and consultant for developing high rise building, offshore structure, water tanks and bridges compared to steel reinforced concrete. This is because prestressed concrete has many advantages over steel reinforced concrete. Some of the advantages are, firstly, the structural elements has a good quality when it was produced in the factory as the quality of the product is assured. Secondly, the usage of prestressed concrete will make the cost of a project becomes more effective as the number of labor required is less since the product is produced in the factory. Thirdly, bridges with longer span can be constructed using prestressed concrete [1]. Basic function of bridges structure is to connect the two lands separated by rivers, valleys, and road but nowadays bridges has become a landmark to an area. As an example Penang Second Bridge in Penang, Sultan Zainal Abidin Bridge in Terengganu and London Bridge in London. In order to preserve the aesthetical value of the landmark, longer span is needed thus it will reduce the number of bridge support.

Normally, bridges with longer span will be constructed stage by stage on site as the monolithic construction is impossible to be done. Hence, the sequence of the construction stages on site need to be studied carefully before the analysis and design process begin. Prestressed concrete bridges can be designed in simply supported and continuous. Designing continuous bridges are more complicated as the line of thrust of the steel may not in the same location of the steel profile thus will create additional moment which is parasitic moment. While simply supported bridges are more easier to design as the line of thrust is same with the steel profile[2]. Therefore, a suitable method to design the steel profile of prestressed bridge need to be studied.

The aim of this study is to determine the process of analysis and design of three span continuous prestressed concrete bridge based on construction stages. The objectives for this study are:

1. To review, understand and analyse the construction sequence of the three span continuous prestressed concrete bridge.

2. To analyse the suitable method to be used in designing the three span continuous prestressed concrete bridge.
3. To analyse and design the three span continuous prestressed concrete bridge by considering the construction sequence.

This study is focusing on three span continuous prestressed Putai Bridge constructed in Sarawak to connect the main road with Baleh Hydroelectric Project site. The overall scope can be pointed as follows:

- The bridge is a symmetrical post-tensioned continuous prestressed bridge with three span.
- The cross-section properties and dimension of the actual bridge has been used throughout this study.
- Load Model 1 and Load Model 3 obtained from BS EN 1991 specification has been used to analyse the traffic loading acted on the bridge.
- Wind load is not considered during analysis stages
- The analysis of this bridges is modeled in two dimesion in StaadPro software according to the construction sequence.
- The bending moment analysed is up to serviceability limit state.

Theoretical Background

The analysis and design of a continuous concrete bridge must take into account the behaviour of the structure under applied load. Loading that always being considered for the bridge analysis are the selfweight of the bridge, the superimposed dead load (wearing coat and parapet) and highway loading based on British Standard. Since Eurocode(EN 1991-2) has been introduced to supersede British Standard(BS 5400-1:1998) , types of loading applied on the structure is taken from Eurocode specification. The worst load combination of Load Model 1 and Load Model 3 analysis will be considered in the design [3].

Prestressed concrete tends to be used for the longer span bridge structure which often means they are built in sequence. Therefore, the actual bending moment produce at the end of construction(service life) is differ from the bending moment which would be expected if the construction is has been build in one go. The designer need to allow for temporary condition and also for the trapped moment that are induced by the construction sequence [4].

At present, there are several method available for designing a continuous prestressed concrete beam such as load balancing method and concordancy method. Both method will not produce parasitic moment as the load-balancing method proposed by T.Y. Lin reduced the analysis to that of a nonprestressed structure in which consideration of secondary moments is essentially bypassed and concordant cable plotted from concordancy method will have a C-line coincidence with c.g.s line thus produce no secondary moment in the beam[2]. Advantage of both methods are load balancing provide a simple analysis and design[2] while concordant profile is more easier to compute, analyse and the design approach is similar to that simply supported beam[5]. Both methods have their own limitation. Limitation of load-balancing method is the uncertainty of percentage of load needed to be balanced by prestressing force[2] while limitation of concordancy method is concordant profile are almost universally uneconomical, frequently requiring some 50 per cent more prestressing steel than a properly designed profile[6].

Secondary moment which also known as parasitic or hyperstatic moment are produced in continuous beam where intermediate support restrict the free deformation of structure. Hence leading to support reaction called secondary reactions. Secondary reactions act like a concentrated loads on simply supported beam. They generate at each section a moment called secondary moment. Secondary moments are secondary in nature but not in magnitude. They can represent a significant portion of the prestressing moment and hence, must be accounted for in design [5].

Methodology

The methodologies conducted to determine the process of analysis and design of three span continuous prestressed concrete bridge based on construction stages for this study are as follows:

Studies the Construction Drawing of Bridge

Every single sheet of Putai Bridge construction drawing has been studied to have a better understanding on the actual shape of the bridge. Apart from that, the studies has been conducted to determine the section of the bridges, dimension of each element exist in the bridge structure and how the structure is going to be construct on site. The concrete grade used to cast each structural element also need to be known.

Review the suitable method available for design

Several methods such as load balancing and concordancy method are available to design a continuous beam. Since designing the continuous beam is more complex compared to simply supported beam, the suitable method need to be adopted. Every methods from textbook is reviewed to select the most suitable and convenient with the time allocated for this study.

Analysis

Before designing the continuous prestressed concrete bridges, several analysis need to be done such as, section geometry analysis, applied load analysis, section adequacy check , and stress limit.

*Section Geometry Analysis.*Putai Bridges has different member such as T-beam, stitch, and crossbeam. Each section need to be analyse to compute the section properties for each member. Each computation can be done using Structural Bridge Design 2014 software. Each section properties is required for modeling the line-beam model.

*Applied Load Analysis.*A line beam is established in Staad.Pro software to derive the distribution of bending moment under different applied loading condition. The loading considered for bridge are the dead load which is the selfweight, superimposed dead load and live load. Live load is the combination of Load Model 1 and Load Model 3. The analysis of bending moment is carried out at two stages, which are transfer stage and service stage. During the transfer stage, the beam and crossbeam act as a simply supported and cantilever respectively. While during the service stage, the beam will act as a continuous structure. The result of bending moments obtained from the Staad.Pro will be extracted and fed into next analysis and designing the prestressed concrete bridge.

*Section Adequacy Check.*With the available section geometry, the adequacy of the section is checked in order to ensure the suitability of the provided section. The bridge consist of composite and non-composite structure. Thus,the section adequacy for both types can be check using the formula stated below:

1. non-composite structure

$$z1\text{, actual} \geq (\alpha Ms - \beta Mi) / (\alpha fcs - \beta ftt)$$
$$z2\text{, actual} \geq (\alpha Ms - \beta Mi) / (\alpha fct - \beta fts)$$

2. composite structure

$$z1\text{, beam actual} \geq \frac{\alpha(Ms - Md)}{(\alpha fcs - \beta ftt) + 1/z1\,(\beta Mi - \alpha Md)}$$

$$z2\text{, comp actual} \geq \frac{\alpha(Ms - Md)}{(\beta fct - \alpha fts) + 1/z2\,(\beta Mi - \alpha Md)}$$

$$z1\text{, comp actual} \geq (Ms - Md) / fcs\text{,slab}$$

Stress Limit. The stress encountered in each critical section due to applied load is checked at every stages. The stress imposed must not reached the allowable stress limit. The stress limit value is calculated from the concrete grade used during construction. The stress limit can be calculated as follows:

1. non-composite structure

Transfer Stage

$$\frac{\alpha Pi}{A} - \frac{\alpha Pie}{z1} + \frac{Mi}{z1} \geq ftt$$

$$\frac{\alpha Pi}{A} + \frac{\alpha Pie}{z2} - \frac{Mi}{z2} \leq fct$$

Service Stages

$$\frac{\beta Pi}{A} - \frac{\beta Pie}{z1} + \frac{Ms}{z1} \leq fcs$$

$$\frac{\beta Pi}{A} + \frac{\beta Pie}{z2} - \frac{Ms}{z2} \geq fts$$

2. composite structure

Stage 1 (Transfer)

$$\frac{\alpha Pi}{A} - \frac{\alpha Pie}{z1} + \frac{Mi}{z1} \geq ftt$$

$$\frac{\alpha Pi}{A} + \frac{\alpha Pie}{z2} - \frac{Mi}{z2} \leq fct$$

Stage 2

$$\frac{\beta Pi}{A} - \frac{\beta Pie}{z1} + \frac{Md}{z1} \leq fcs$$

$$\frac{\beta Pi}{A} + \frac{\beta Pie}{z2} - \frac{Md}{z2} \geq fts$$

Stage 3 (Service)

$$\frac{\beta Pi}{A} - \frac{\beta Pie}{z1} + \frac{Md}{z1} + \frac{Ms\text{-}Md}{z1,beam} \leq fcs$$

$$\frac{\beta Pi}{A} + \frac{\beta Pie}{z2} - \frac{Mi}{z2} - \frac{Ms\text{-}Md}{z2,comp} \geq fts$$

$$\frac{Ms\text{-}Md}{z1,comp} \leq fcs,slab$$

The value of prestressing force used in the transfer stage is calculated from the number of tendon required during that stage. Furthermore, the value of initial moment (Mi) is obtained from the bending moment resulted from simply supported beam analysis.

Designing Preliminary Prestressed Concrete Beam

After going through all analysis and obtaining the result, these values are used in design of prestressed concrete bridge. The design of the prestressed concrete beam is done using Excel spreadsheet. The number of tendon required at each critical section such as midspan and crossbeam of the support is calculated from the minimum prestress force required. There are two set number of tendon calculated at each critical section.

Results and Discussion

This section focus on the construction sequence of the bridge and analysis and design of the continuous bridge based on construction sequence.

Construction Sequence

Six stage of construction sequence will be done during the construction on site.

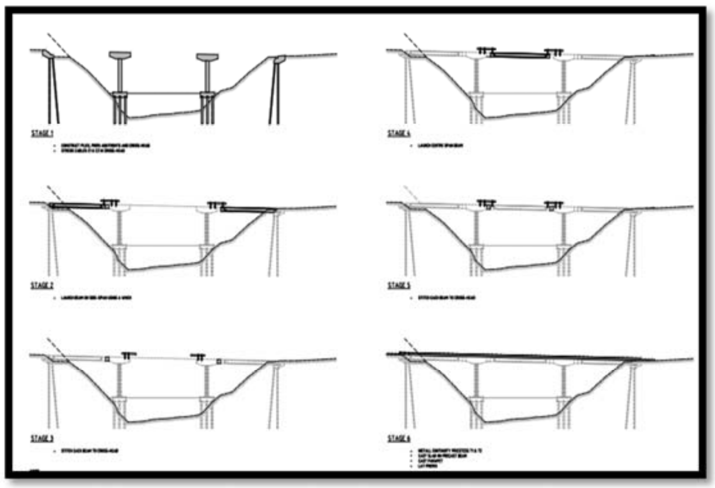


Figure 1: Stages of Construction Sequence

At stage 1, crossbeam will be cast in situ on the top of the support using concrete grade 40 MPa. Stage 2 shows the pre-cast beams about 28 900 mm long is installed on both side of the bridge. During the transferring process, the beams will act as a simply supported beam and bear its own selfweight. In the meanwhile, before the beams and crossbeam jointed as a one structure by stitching, crossbeam acted as a cantilever beam and bear its own selfweight plus the weight of crane and beam. Stage 4 shows the pre-cast beam about 34 000 mm long is installed in the middle of the bridge. The concept still follows the previous beam. On the last stage which is stage six, the deck and parapet is installed. On this stage, all structural element become continuous. It can be conclude that, a sufficient number of tendons must be provided on the beam based on the critical bending moment resulted from the stage 1 or Stage 6. While number of tendon required for service stages will be design based on stage 6.

Design Method

After doing various study on the method of designing continuous beam, a suitable method adopted in this study are concordancy method. This method is selected because it has a simple step of calculations and calculation of the parasitic moment is not required. Concordancy method will produce a concordant cable that located in the line of the thrust. Thus, parasitic moment would not exist in the continuous beam. In conclusion, Concordancy method will be used during this study.

Applied Load Analysis

As mentioned in the previous section, the analysis of applied load is conducted on transfer and service stages.

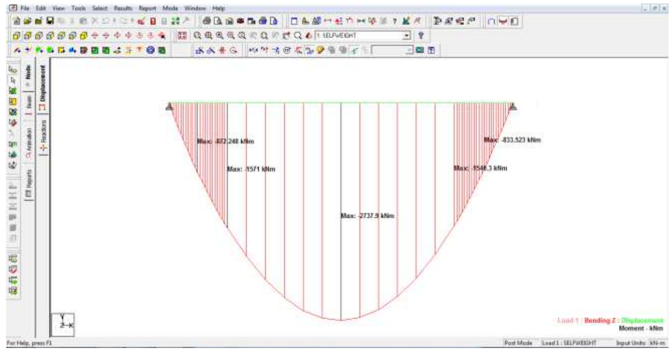


Figure 2: Bending moment at beam 1

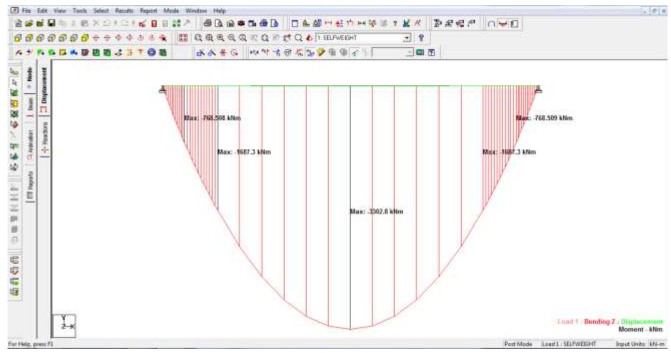


Figure 3: Bending moment at beam 2

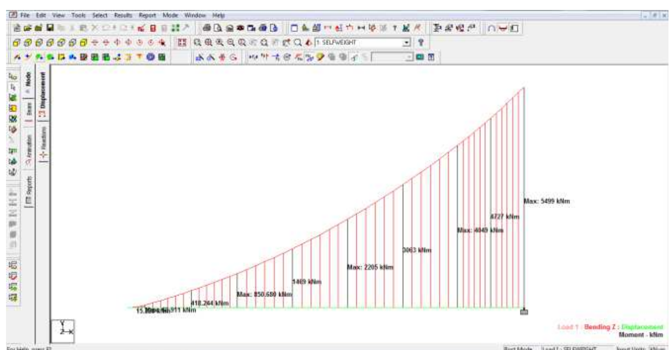


Figure 4: Bending moment at crossbeam

The load applied on the beam 1 and 2 is dead load (selfweight) while load applied on the crossbeam are dead load and crane weight.

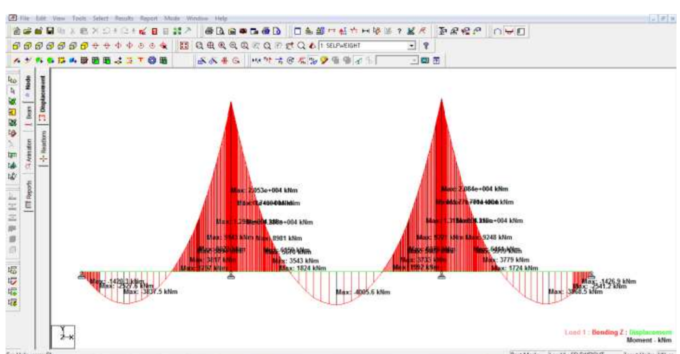


Figure 5: Bending moment due to selfweight at service stage

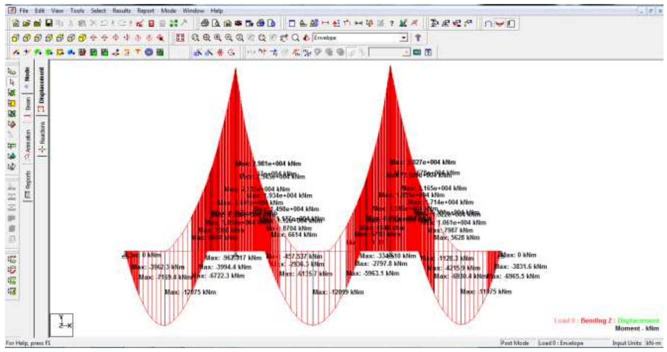


Figure 6: Bending moment envelope due to applied load at service stage

Table 1: Maximum bending moment value on transfer stage and service stage

Section/Stages	**Max Bending Moment due to selfweight (kNm)**	
	Transfer (1)	Service (6)
Beam 1	2737.9	1698
Beam 2	3302.8	1833
Crossbeam	-5499	-11282

Since the bending moment at beam1 and 2 is critical on transfer stage , the value will be used for designing the number of tendons and prestress force needed at the stage 1 construction sequence. While, bending moment at crossbeam is critical at service stage. However, the value of bending moment at transfer will be used. Providing tendons and prestress force more than required will resulting in failure in stress limit.

Cable Profile

Concordant steel profile has been plotted by using the data obtained from previous analysis of continuous bending moment envelope. The method of concordancy is applied to plot the steel profile.

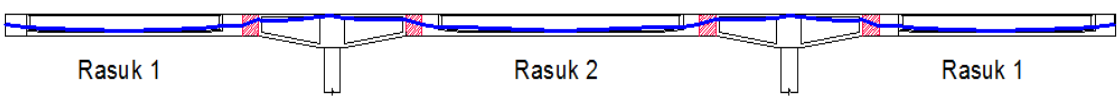


Figure 7: Concordant steel profile

Table 2: Steel profile measured from the top of the structure

x(m)	**0**	**2.4**	**4.9**	**14.45**	**24**	**26.5**	**28.9**	**30.9**	**31.3**	**33.4**	**35.9**
profil(mm)	1027	1313	1468	1740	1466	1248	1153	466	598	630	586
x(m)	**38.4**	**39.9**	**41.4**	**43.9**	**46.4**	**48.5**	**48.9**	**50.9**	**52.9**	**55.9**	**67.9**
profil(mm)	307.2	150	358	495.4	524.5	538.7	479.9	1062.8	1297.1	1412.5	1742.5

The steel profile produce is not the most economical as the steel profile at the midspan of the beam 1 and 2 is not at the maximum feasible sag. While maximum pratical eccentricities is applied at the centre of the support [5]. However, this steel profile will induced no reaction which is parasitic moment on intermediate support[2]. Thus, it reduce the calculation steps required to design the continuous prestressed bridge.

Prestress Force and Number of Tendons

Figure 8 shows the minimum prestress force while Figure 9 shows the number of tendons required at each structural element during the transfer and service stages by using the eccentricities of the previous steel profile and the analysed bending moment.

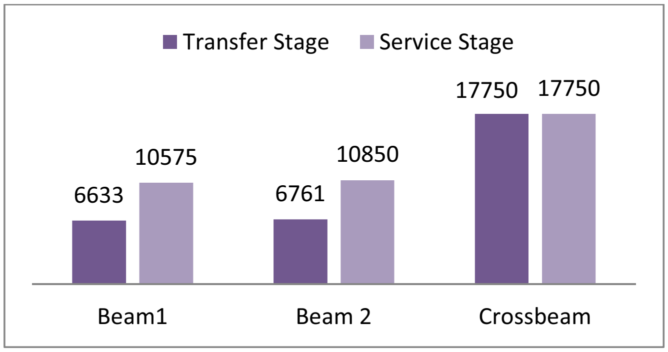


Figure 8: Minimum prestress force required at each structural element

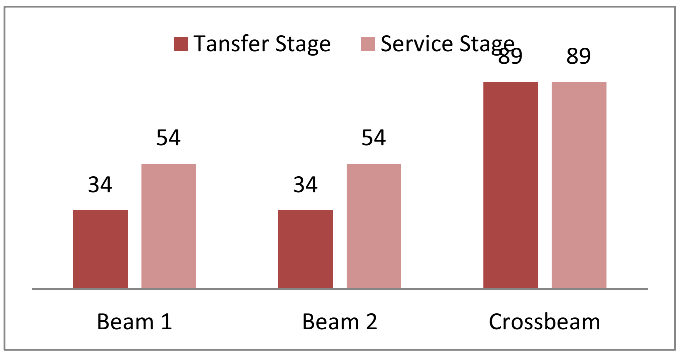


Figure 9 : No of tendon required at each structural element

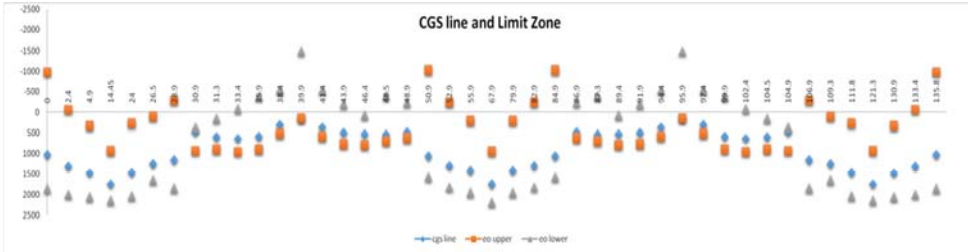
It can be shown in the Figure 9 that the value of prestress force required for Beam 1 and Beam 2 at transfer stage is lower than value of prestress force required at service stages. On the contrary, the minimum value of prestress force required at crossbeam is equal at both stages.

Number of tendons required by Beam 1 and 2 are 34 and 54 at transfer and service stage respectively. Therefore, during transfer stage,34 number of tendons will be installed at Beam 1 and 2 while the remaining of 20 tendons will be installed throughout the bridge at the service stage. Since the number of tendons required by Crossbeam at transfer and service stage are 89, all tendons at crossbeam is installed at once. The tendons installed will be used to sustain loading at transfer and service stage.

Zone Limit

Figure 10 shows the upper and lower limit of the zone limit. From the figure, it can be shown that steel profile (blue line) is located inside the zone limit. It can be conclude that the cable profile provided in the study is appropriate and suitable to be used.

It can be seen in the Figure 10 that upper and lower limit is located above and below the beam structural element. Contrarily, the upper and lower limit is located below and above the crossbeam structural element. Since crossbeam act as a support in this structural bridge, the top of the crossbeam will experience tension stress while bottom of crossbeam will experience compression stress. While bottom and top of beams will experience tension and compression stress. It can be conclude, the upper limit is the limit for compression stress and the lower limit is the limit for tension stress.



*orange line = (eou)upper limit , grey line = (eol)lower limit, blue line = steel profile

Figure 10: Upper and Lower Limit zone

Conclusion

In conclusion, the construction sequence analysis play an important role in analysing and designing the continuous prestressed concrete bridge. The designer must take into consideration the construction stages along the analysis and design process. From this study, it can be conclude that :

1. The construction sequence on site will give effect to the analysis and design process of the three span continuous prestressed concrete bridge.
2. The beam and crossbeam need to be analyse as a simply supported and cantilever state during the transfer stage or the first stage of construction sequence. While , the bridge need to be analyse in a continuous state on the service stage or the six stage of construction sequence.
3. The suitable method which has a simple step of calculations that can be used to design continuous prestressed concrete bridge is Concordancy method.
4. The appropriate steel profile can be achieved using Concordancy method since it is located inside the Zone Limit.
5. The tendons in beams will be installed at two stages while tendons in crossbeam will be installed at once.

In light of limitation of the present study, a few areas were identified where further study is required ;

1. The moment distribution due to live load need to be analyse using more accurate software such as grillage model in Staad.Pro beava. A line-beam model has been used to analyse the live load moment distribution in this study.
2. The short term and long term prestress loss effect need to be calculated. In this study, the short term and long term prestress loss is assume as 10% and 25 % respectively.
3. Analysis and design of the continuous prestressed concrete beam need to be calculate at each 0.1L of the bridge to acquire most accurate result. In this study the analysis and design is done at each critical part due to time constrain.

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