공학석사학위논문

Determination of Dynamic Amplification Factor and Reliability Assessment for Accidental Rupture of Cables

케이블 부재의 급진적 파단에 대한 동적증폭계수 산정 및 신뢰도 평가

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ABSTRACT

In this study, Dynamic Amplification Factor(DAF) is determined for the results of quasi-static analysis to reproduce the results of dynamic analysis properly and the safety of the adjacent cables is confirmed when the cable ruptures. There are two methods to check the safety of cables about cable rupture: Quasi-static analysis; Dynamic analysis. Dynamic analysis is the exact method relatively between two methods and the results of quasi-static analysis should reproduce the results of dynamic analysis. Therefore, it is important to determine exact DAF in order to use quasi-static analysis. In this study, not the meaning of DAF term itself but the similarity of the results which are obtained by two analyses is focused. First of all, dynamic analysis is performed and the result is set up as the standard. The results of quasi-static analysis are compared with that of dynamic analysis altering DAF. Prototype cable-stayed bridge, Incheon bridge and 2nd Jindo bridge which have various lengths of main girder are used as the examples of cable-stayed bridge and Yisunshin bridge, Ulsan bridge and New Millennium bridge are used as the examples of suspension bridge. Tension of the cables and moment of the girders are used as the standard of comparison and DAF is determined when the error between the results of two analyses is minimized. In addition, the reliability assessment about tension of the other cables is performed when the cable ruptures. The same examples which are used for the determination of DAF are identically selected for the reliability assessment. The cross-sectional area decreases using the simple Target Configurations Under Dead loads to design the cables suitable for Korean Highway Bridge Design Code(Limit State Design)-Cable Supported Bridge(2015) and the reliability assessment is performed about the tension of the cables.

KEY WORDS:
Dynamic amplification factor, Quasi-static analysis, Dynamic analysis, Reliability assessment, Cable rupture, Limit state Design

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1. Introduction

1.1. Research Background

Recently as technology of bridge engineering has been developed and demand of long-span bridges has increased, the number of cable bridges is increasing. There are higher probability to occur extreme events such as ship collision, cable exchange and cable rupture in cable bridges.

There are several accidents related to cable rupture among the extreme events in domestic and foreign cable bridges. In 1999, the cable socket of Ji-Lu Bridge was damaged in Chi-Chi Taiwan Earthquake. In 2005, the cable was ruptured in Rion Antirion Bridge in Greece due to lightning strike. In 2007, fire caused by the car accident damaged the cable of Mezcala Bridge in Mexico. In 2015, the cables were also affected dangerously by fire in Seohae Bridge in Korea, too. In this case, a cable was ruptured and two cables got damaged.

Although the cross section of cable elements is so small, they support the huge loads relatively. So the elements are important parts in cable bridges. If problems regarding the elements occur as a consequence of natural disasters including fire and thunder, it causes the dynamic effect to the entire cable bridge. Consequently, the Recommendation should contain the regulation that confirms the effect of cable rupture to structure.

1.2 Regulation for Cable Rupture

There are two methods to check safety of the structure for cable rupture in the recommendations including Korean Highway Bridge Design Code(Limit State Design)-Cable Supported Bridge(2015)(KHBDC), PTI Recommendations(2012)(PTI) and SETRA Recommendations(2002)(SETRA): quasi-static analysis of Cable Rupture and dynamic analysis of Cable Rupture. The best method to confirm safety of cable is dynamic analysis in the time domain because dynamic effect about the sudden cable rupture can be considered directly in dynamic analysis. However, quasi-static analysis using Dynamic Amplification Factor(DAF) can be performed. It is assumed that single cable ruptures at a time in the both methods and all cables should be checked.

Table 1.1 summarizes DAF and load combination for cable rupture in domestic and foreign recommendations. In PTI(2012), cable loss dynamic forces is multiplied by the load factor 1.1. The types of cable rupture are classified into two categories: Progressive Rupture and Accidental Rupture. Different DAFs are used in two categories. Design Guidelines for Steel Cable-Supported Bridges(2006)(DGSCB) and KHBDC(2015) use 2.0 and 1.5 as DAF respectively. In brief, DAF is selected as 1.5 or 2.0 in the recommendations and quasi-static analysis using DAF can be utilized. Additional research is needed for application to the complex cable bridges, because DAF is calculated from the one degree of freedom analysis.

Table 1.1. Load combination and DAF for major design codes

Recommenda-tions	Load Combination	DAF
PTI (2012)	$1.1DC + 1.35DW + 0.75(L + I) + 1.1CLDF$ $CLDF$: Cable Loss Dynamic Forces	DAF=2.0
SETRA (2002)	$0.75TS + 0.40UDL$ TS : Tandem System UDL : Uniformly Distributed Load	Accidental Rupture DAF=2.0 Progressive Rupture $1.5 \leq \mathrm{DAF} \leq 2.0$
DGSCB (2006)	$1.0D + 0.5(L + I) + PS2$ $PS2$: Cable Loss Dynamic Forces	DAF=2.0
KHBDC (2015)	$\gamma_p(DC + DW) + 0.75(LL + IM) + PS2$ $PS2$: Cable Loss Dynamic Forces	DAF=1.5

1.3 Research Purpose

Several researchers have already reported(Ruiz-Teran et al. 2007; Park 2007; Kim et al. 2012; Na et al. 2014; Ahn 2015) if proper DAF have been used in the recommendations. In the previous researches, the definition of DAF is focused. DAF in the previous researches is defined as the ratio of the difference between the maximum value of dynamic response and the value of static response before rupture to the difference between the value of static response after rupture and the value of static response before rupture.

$$\mathrm{DAF} = \frac{\mathrm{Max}\left(\left|\Delta_{\mathrm{Dyn1}}\right|, \left|\Delta_{\mathrm{Dyn2}}\right|\right)}{\left|\Delta_{\mathrm{Static}}\right|} \tag{1.1}$$

Δ_{Dyn1}, Δ_{Dyn2} and Δ_{Static} used in Eq. (1.1) can be defined by Fig. 1.1. In other words, the difference between the maximum value of dynamic response and the value of static response before rupture means a larger value between Δ_{Dyn1} and Δ_{Dyn2}.

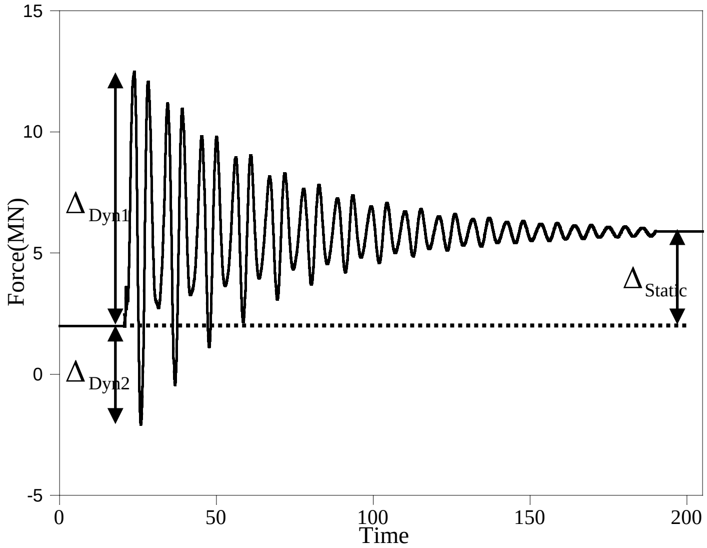


Fig. 1.1. Sample dynamic behavior due to cable rupture

In this study, DAF applied in quasi-static analysis to describe the result of dynamic analysis is calculated unlike the previous research which is focused on the definition of DAF. First of all, dynamic analysis is performed in the time domain when one cable ruptures. The maximum tension of the other cables and the maximum and minimum moment of the girder elements are recorded during the analysis. Second, quasi-static analysis adjusting DAF is carried out and DAF is determined when there is the smallest error between quasi-static analysis and dynamic analysis.

Further research is needed to calculate the failure probability of adjacent cables if a cable breakage happens. So, the probability of failure can be calculated in reliability assessment implementing load combination and DAF of the recommendations.

2. Cable Rupture Simulation Method

2.1. Quasi-Static Analysis for Cable Rupture

The method to simulate a momentary cable rupture using quasi-static analysis is as follows. Above all, static analysis with dead load of the bridge and live load of all the lanes is performed and tension of the cable which is selected to be ruptured is calculated. Then, the cable element is removed and nodal forces equal to the tension of the ruptured cable are added at the cable anchor. To consider the effect of cable rupture, the forces are equal to the tension of the ruptured cable multiplied by DAF in the opposite direction of the tension. Finally, static analysis is performed and the responses of the cable and girder element are checked. In other words, after the ruptured cable is removed, quasi-static analysis applying the forces which is the same values as the tension of the ruptured cable multiplied by DAF minus 1 is completed.

In this study, the method of Elastic Catenary Cable(Kim and Lee 2001; Kim et al. 1989) is used to calculate the stiffness matrix in quasi-static analysis because it has a high degree of accuracy.

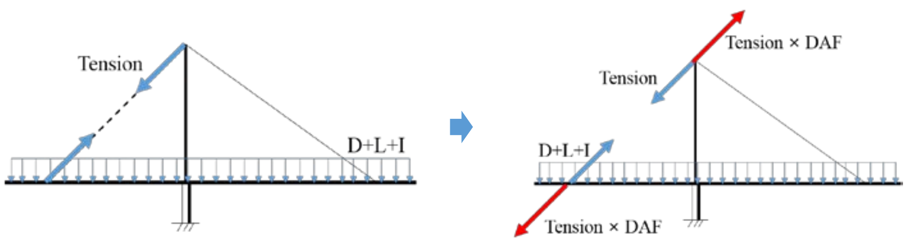


Fig. 2.1. Quasi-static analysis applying DAF for cable rupture

2.2. Dynamic Analysis for Cable Rupture

The method to simulate a momentary cable rupture using dynamic analysis is as follows. First, static analysis with dead load of the bridge and live load of all the lanes is performed and tension of the cable which is selected to be ruptured is calculated. The cable element is removed and nodal forces equal to the tension of the ruptured cable at the cable anchor are added. The nodal forces linearly decrease zero during a short period of time Δt to describe the momentary cable rupture.

In this study, Constant average acceleration method which is one of Newmark's β methods has been employed in the time domain(Chopra 2012). 0.4% Rayleigh Damping has been assumed and the method of Equivalent Modulus of Elasticity has been used to calculate the stiffness matrix in dynamic analysis. It is suitable for dynamic analysis, since the method of Equivalent Modulus of Elasticity has the advantage of a fast computation speed(Ernst 1965; Chopra 2012).

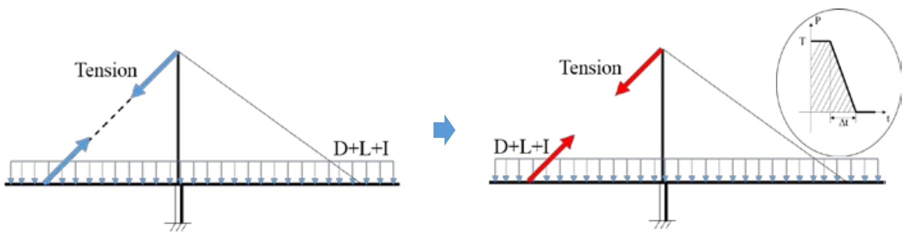


Fig. 2.2. Dynamic analysis for cable rupture

2.2.1. Determination of Time about Rupture Occurrence

The rupture of a cable can be classified as the accidental rupture or the progressive rupture according to rupture occurrence time. If the progressive rupture of cable happens, there is not a huge dynamic response in the structure because of long rupture occurrence time. Therefore, the accidental rupture which causes more enormous dynamic response is focused in this study.

In PTI(2012), DGSCB(2006) and KHBDC(2015), there is not a regulation related to the rupture occurrence time. In SETRA(2002), the rupture is classified as the accidental rupture and the progressive rupture. The different DAF is applied as the type of the rupture. However, there is also not a standard to distinguish between the accidental rupture and the progressive rupture in SETRA(2002). Therefore, the definition of rupture occurrence time is needed to distinguish two types of the rupture.

The method to determine rupture occurrence time for the accidental rupture is as follows. Dynamic analysis is performed and the maximum tension of the adjacent cables is recorded when a cable ruptures with the occurrence time from 0.001sec to 10 sec. The accidental rupture occurrence time is determined when the maximum tension does not increase anymore. It is assumed that the maximum tension is already converged, when the error between the convergent value of the maximum tension and the maximum tension is less than 1%. Because the dynamic response in the area close to ruptured cable is greater than that in the area far from ruptured cable, the decision of the occurrence time is based on the tension of the adjacent cables.

In case of the cable-stayed bridge, 2nd Jindo cable-stayed bridge and prototype cable-stayed bridge are used as examples and the cable at one sixth point of the main span is selected as a ruptured cable to determine the occurrence time. In case of the suspension bridge, Yisunshin suspension bridge and Ulsan suspension bridge are used as examples and the cable at a quarter point of the main span is selected as a ruptured cable unlike the cable-stayed bridge.

Fig. 2.3(a), (b), (c) and (d) are the results of dynamic analysis with the occurrence time from 0.01sec to 10sec. The occurrence time of the cable-stayed bridge is determined as 0.1sec according to Fig. 2.3(a) and Fig. 2.3(b). Unlike the results of the cable-stayed bridge, the maximum tension of the adjacent cable is converged when the occurrence time is 0.01sec according to Fig. 2.3(c) and Fig. 2.3(d). To apply the identical result in two types of bridges, the accidental rupture occurrence time is determined as 0.01 sec.

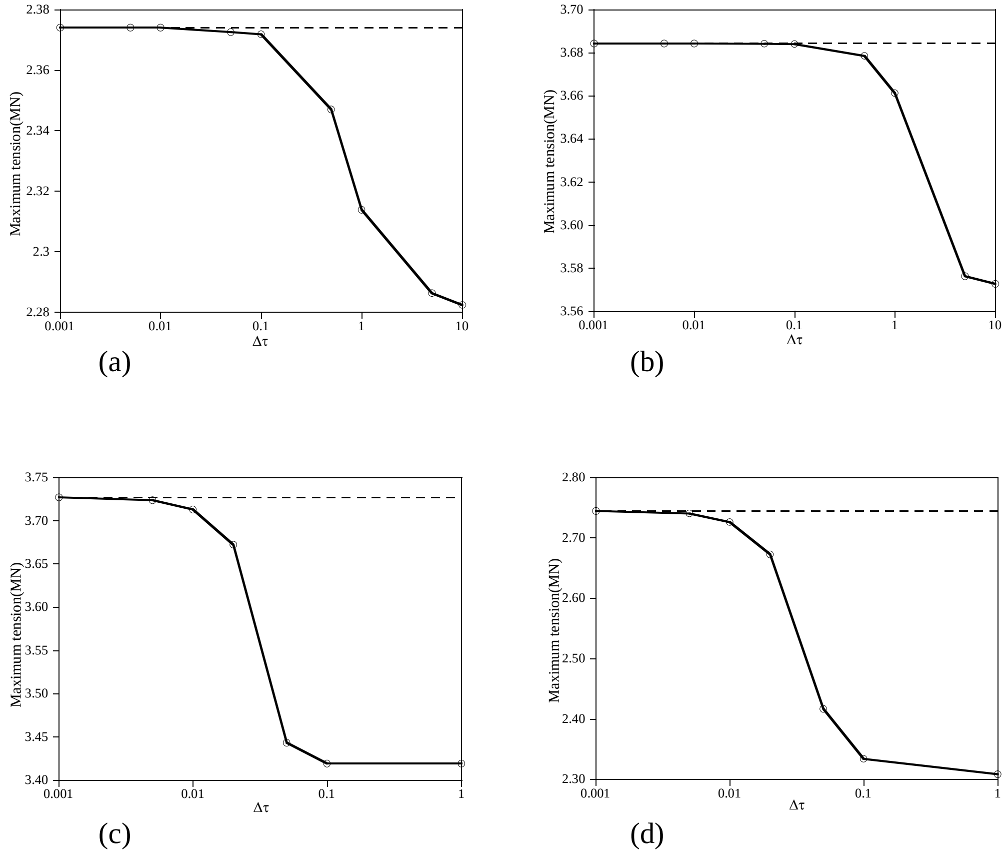


Fig. 2.3. The maximum tension of the adjacent cable or hanger according to the occurrence time: (a) 2nd Jindo bridge; (b) prototype cable-stayed bridge; (c) Yisunshin bridge; (d) Ulsan bridge

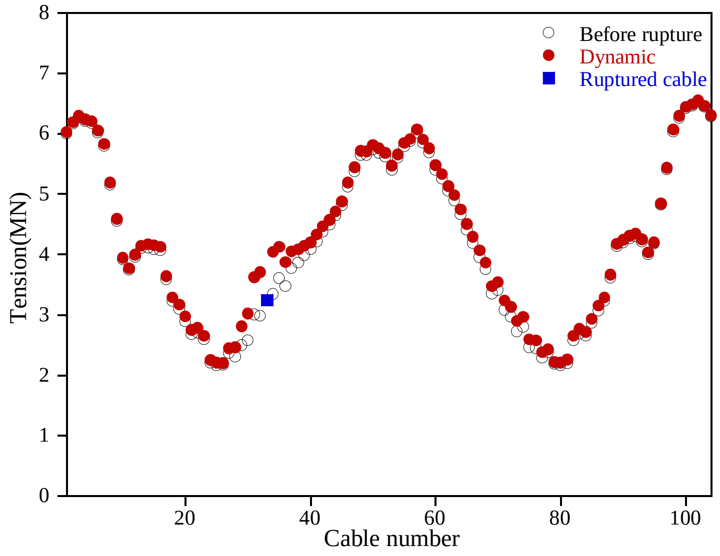
3. Determination of DAF

3.1. Determination standards of DAF

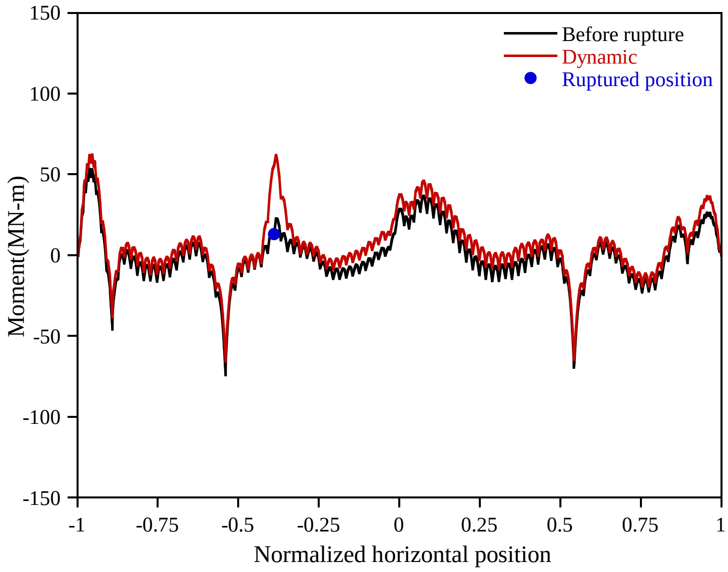
As mentioned before briefly, quasi-static analysis and dynamic analysis are performed and the result of quasi-static analysis is compared with that of dynamic analysis to decide DAF. The tension of cables and the moment of girder are selected as a standard of comparison among various responses. The maximum of cable tension and the maximum and minimum of girder moment are recorded in dynamic analysis for the comparison. Similarly, tension of cables and moment of girder elements are recorded altering DAF in quasi-static analysis.

In Fig. 3.1, the response of static analysis before rupture is compared with that of dynamic analysis after rupture in terms of the cable tension and the girder moment in Incheon bridge. Because there is not a great change in the area far from the ruptured cable according to Fig. 3.1, the range of area in this study is limited to the area close to the ruptured cable. Therefore, DAF is determined to minimize the error between quasi-static analysis and dynamic analysis in terms of the tension and the moment in the area near the ruptured cable. If the difference between the result of quasi-static analysis and dynamic analysis is large, DAF is decided to present that the response of quasi-static analysis is greater than that of dynamic analysis.

In this section, quasi-static analysis and dynamic analysis are performed under KHBDC(2015) and the load combination Accidental Limit States(ALS) 3 is applied.



(a)



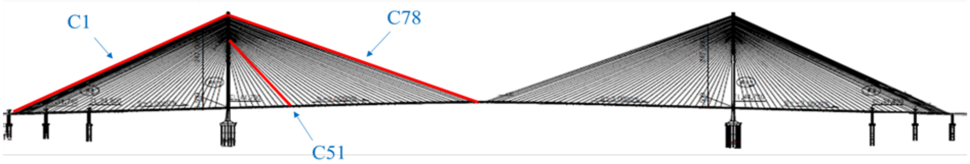
(b)

Fig. 3.1. The response before and after cable rupture at one sixth point of Incheon bridge's main girder: (a) cable tension; (b) girder moment

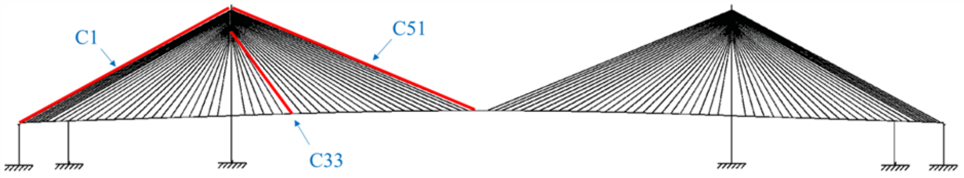
3.2. DAF for Cable-Stayed Bridge

In this study, similarity between the results of two analyses is focused. Therefore, various cases of bridges should be needed to calculate exact DAF. In Fig. 3.2, there are three examples which have different lengths of a main span for cable-stayed bridge: prototype cable-stayed bridge which has a 1200m main span, Incheon bridge which has a 800m main span and 2^{nd} Jindo bridge which has a 344m main span. In three cable-stayed bridge, the numbers of installed cables are 312, 208 and 60 respectively.

The outermost cable, the cable located at one sixth point of the main span and the cable located at a half point of the main span is selected as the ruptured cable because the cables are expected to cause great dynamic responses. Cables are given the number from left to right to call each stay cable.



(a)



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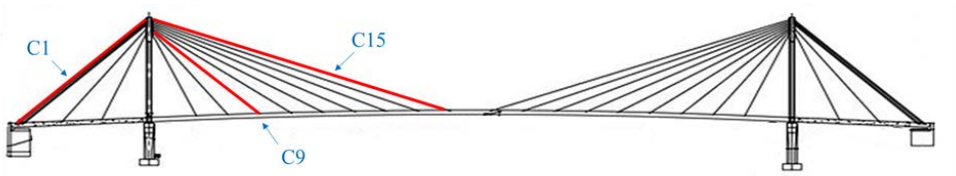


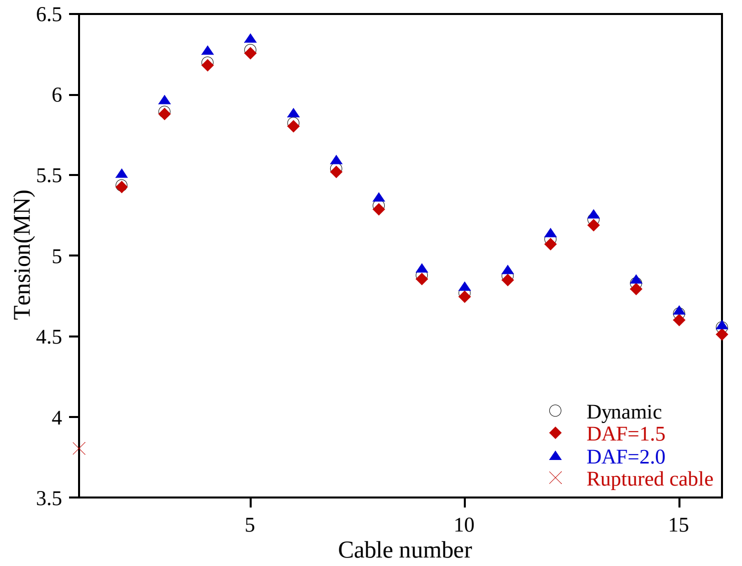
(c)

Fig. 3.2. Longitudinal section view and ruptured cables of cable-stayed bridges:

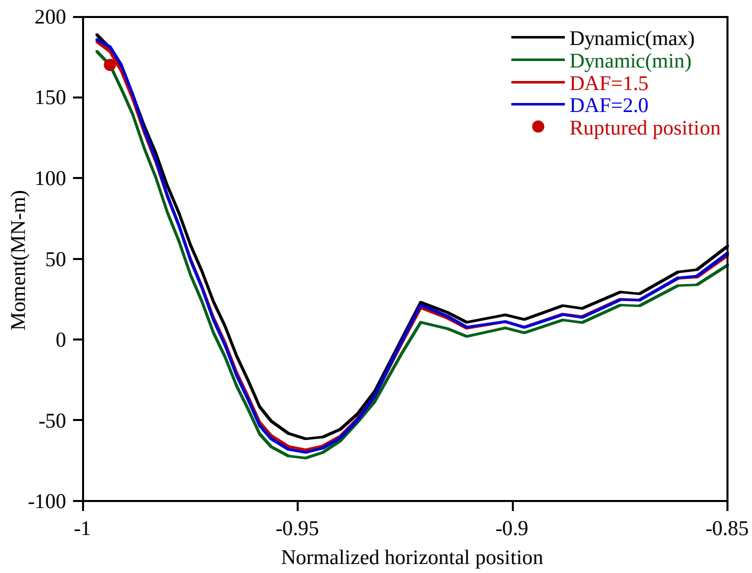
(a) prototype cable-stayed bridge; (b) Incheon bridge; (c) 2nd Jindo bridge

Fig. 3.3, Fig.3.4 and Fig. 3.5 show the results of quasi-static analysis and dynamic analysis as the cable rupture located at the outermost, one sixth point of the main span and a half point of the main span respectively in prototype cable-stayed bridge. There are some differences case by case, but 1.5 is suitable for DAF in terms of cable tension and girder moments in the cable-stayed bridge. The response of quasi-static analysis applying 2.0 as DAF is evaluated excessively compared with the responses of dynamic analysis in the adjacent area. In the area far from the ruptured cable, the results of quasi-static analyses are almost same regardless of DAF.

Fig. 3.6, Fig.3.7 and Fig. 3.8 show the results of two analyses as the rupture occurs to the cable located at the outermost, one sixth point of the main span and a half point of the main span respectively in Incheon bridge. In Fig. 3.9, Fig. 3.10 and Fig. 3.11, there are the results of two analyses as the rupture occurs to the cable located at the outermost, one sixth point of the main span and a half point of the main span respectively in 2nd Jindo bridge, too. There are similar tendencies in Incheon bridge, 2nd Jindo Bridge and prototype cable-stayed bridge. In summary, 1.5 is the appropriate value as DAF in cable-stayed bridge.

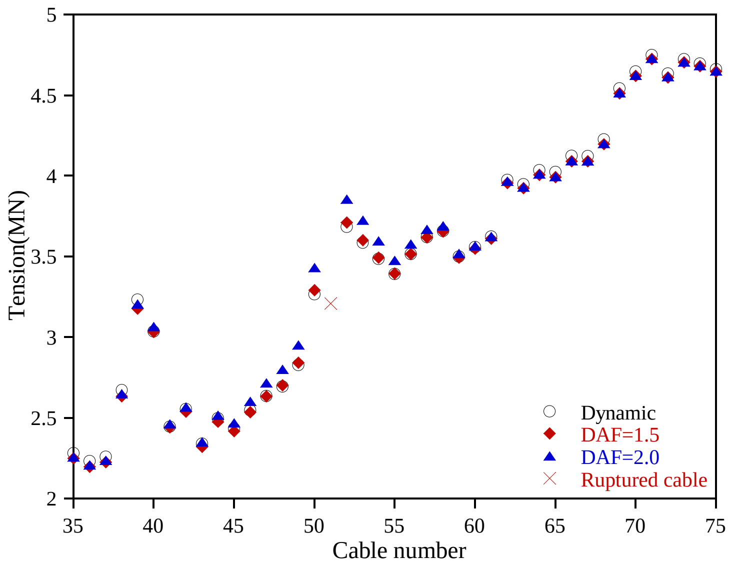


(a)



(b)

Fig. 3.3. Cable rupture located at the outermost point of prototype cable-stayed bridge’s main girder: (a) cable tension; (b) girder moment



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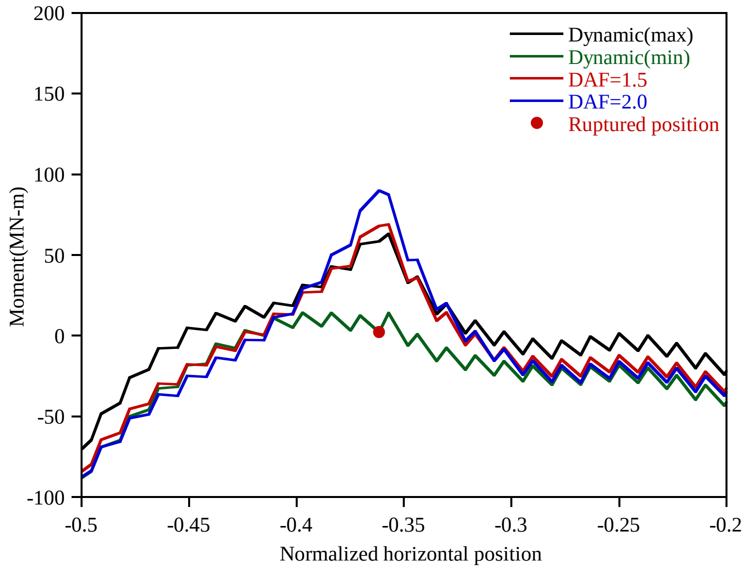
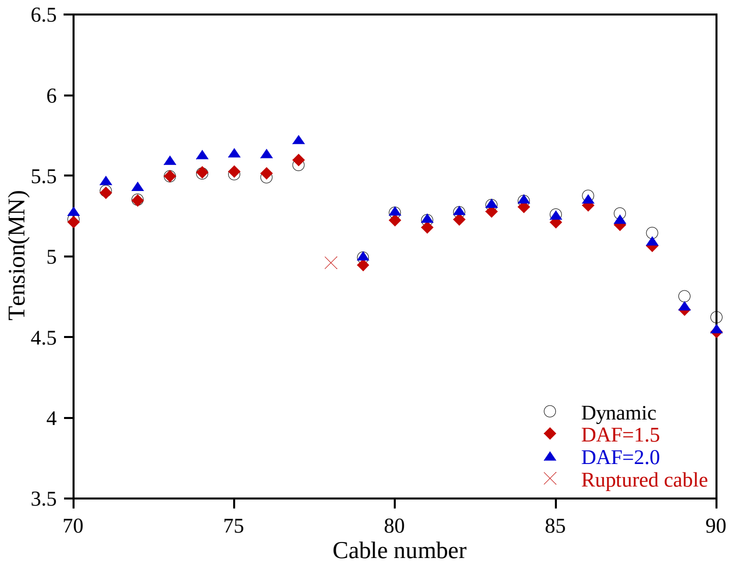


(b)

Fig. 3.4. Cable rupture located at one sixth point of prototype cable-stayed bridge's main girder: (a) cable tension; (b) girder moment



(a)

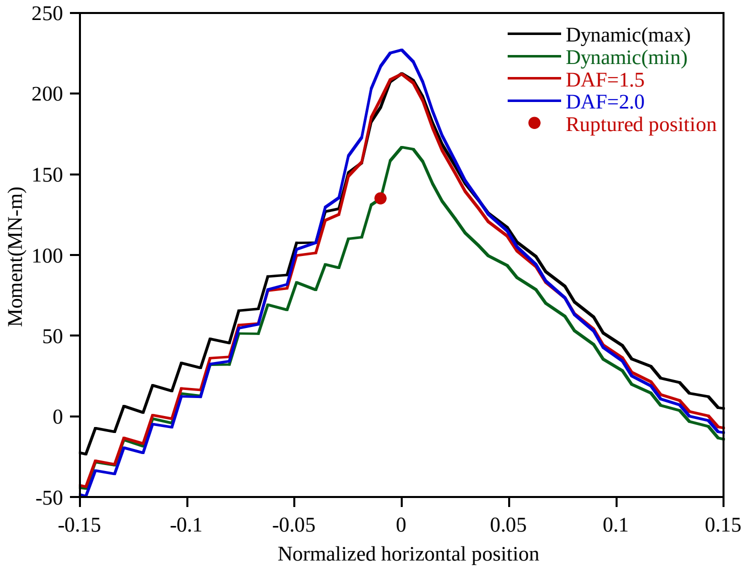


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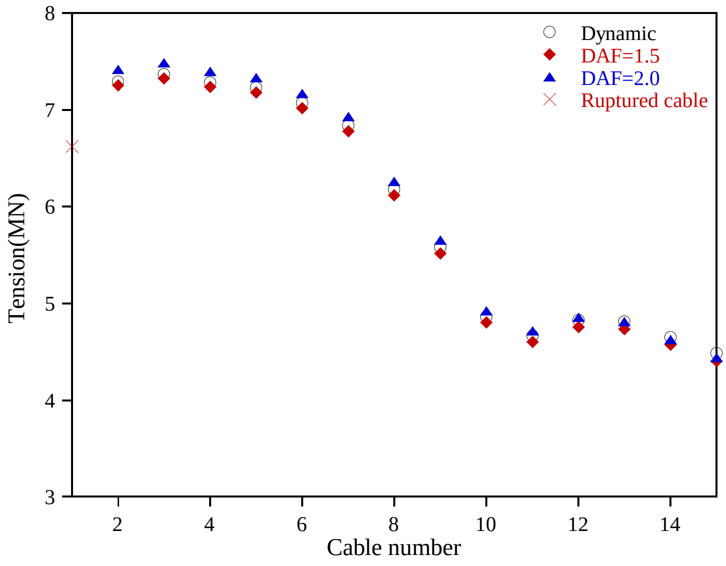
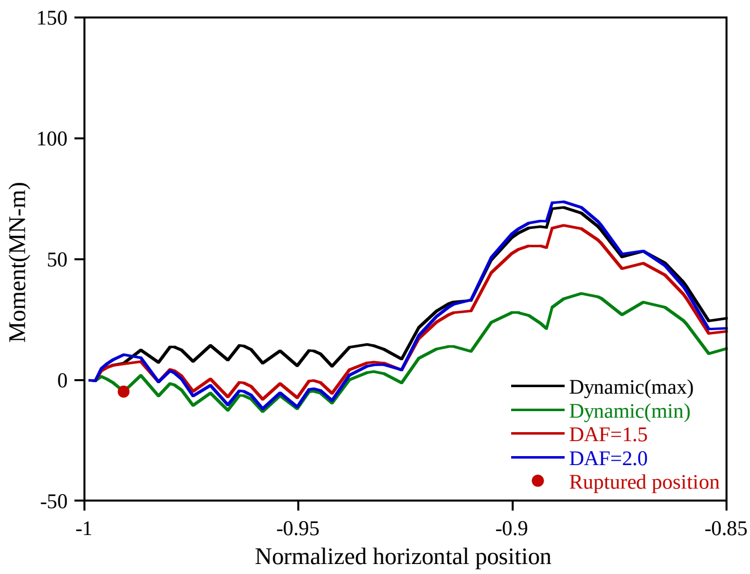
Fig. 3.5. Cable rupture located at a half point of prototype cable-stayed bridge's main girder: (a) cable tension; (b) girder moment

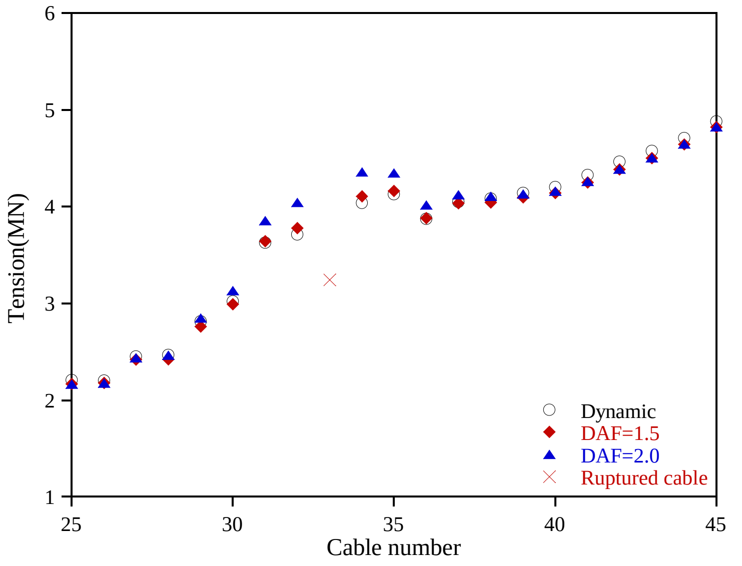


(a)

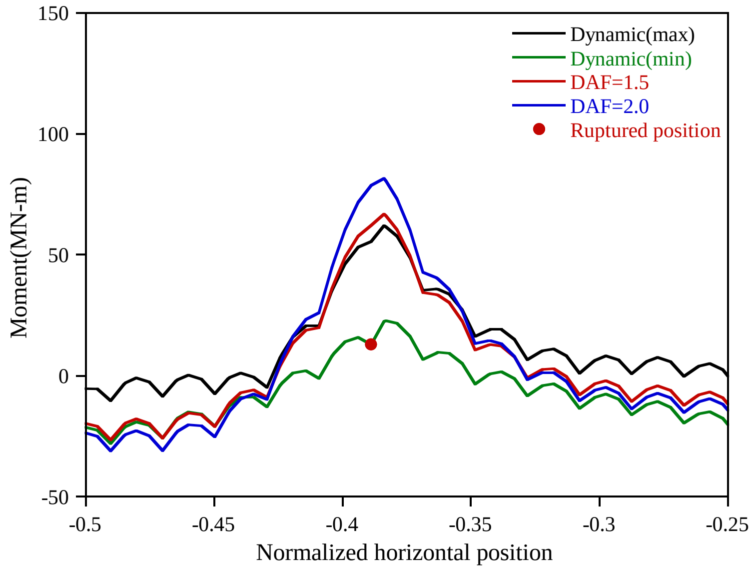


(b)

Fig. 3.6. Cable rupture located at the outermost point of Incheon bridge’s main girder: (a) cable tension; (b) girder moment



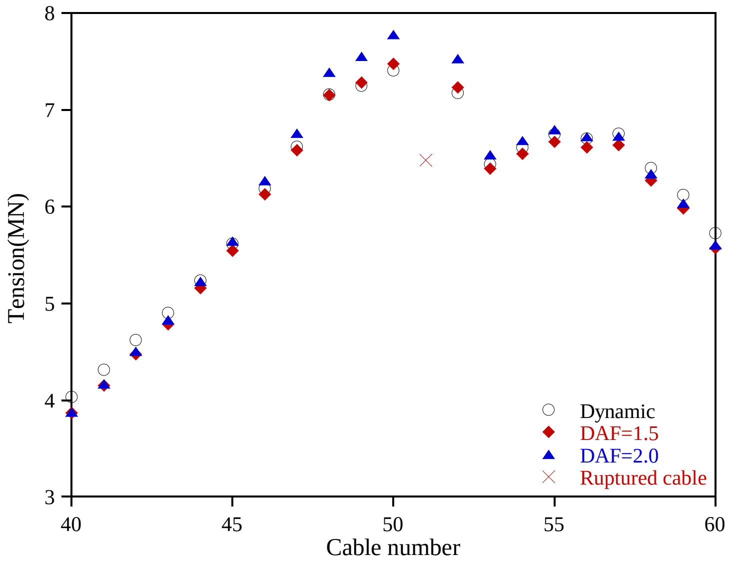
(a)



(b)

Fig. 3.7. Cable rupture located at one sixth point of Incheon bridge's main girder:

(a) cable tension; (b) girder moment



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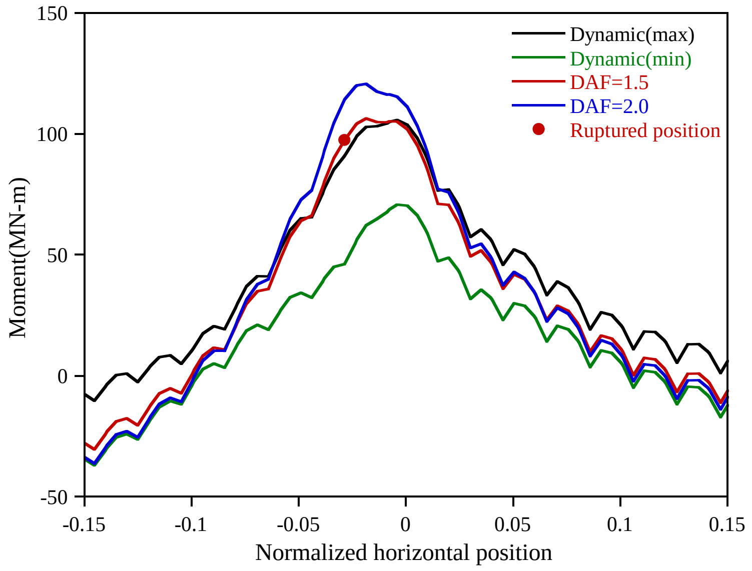
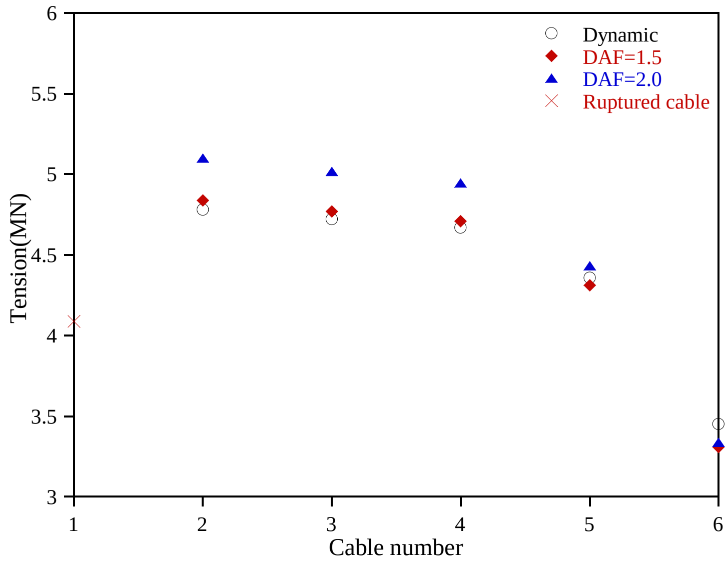


(b)

Fig. 3.8. Cable rupture located at a half point of Incheon bridge's main girder:

(a) cable tension; (b) girder moment



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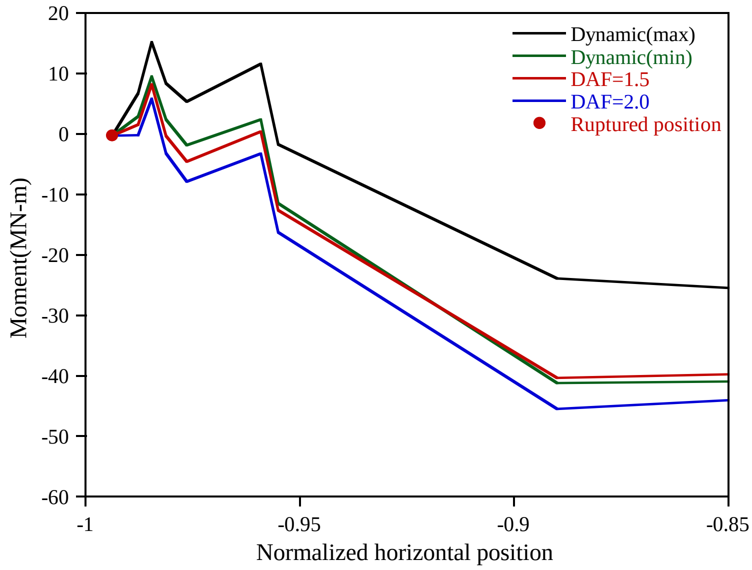
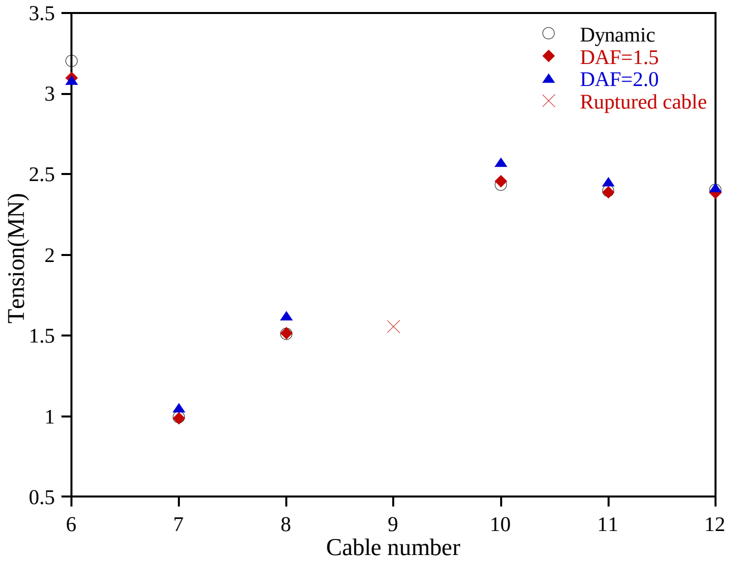


(b)

Fig. 3.9. Cable rupture located at the outermost point of 2nd Jindo bridge's main girder: (a) cable tension; (b) girder moment



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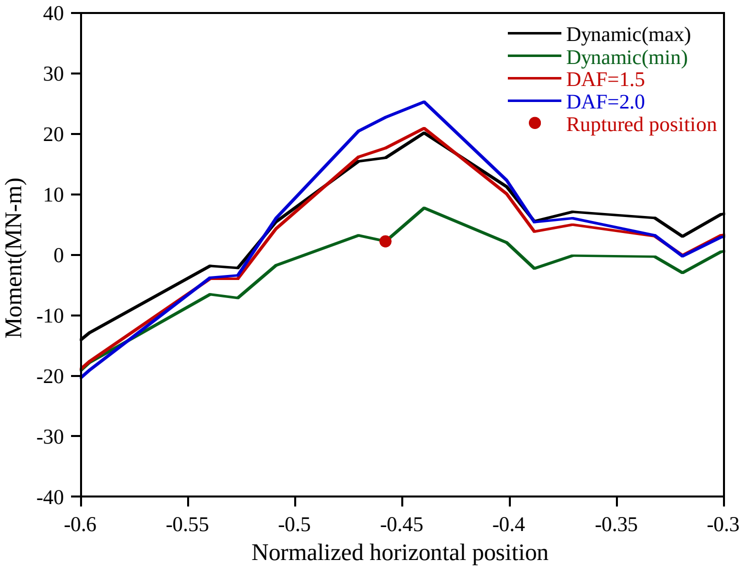
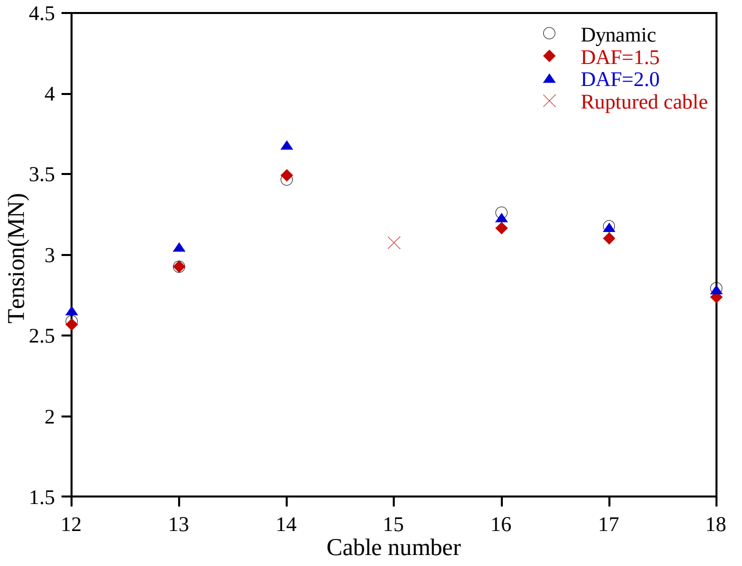
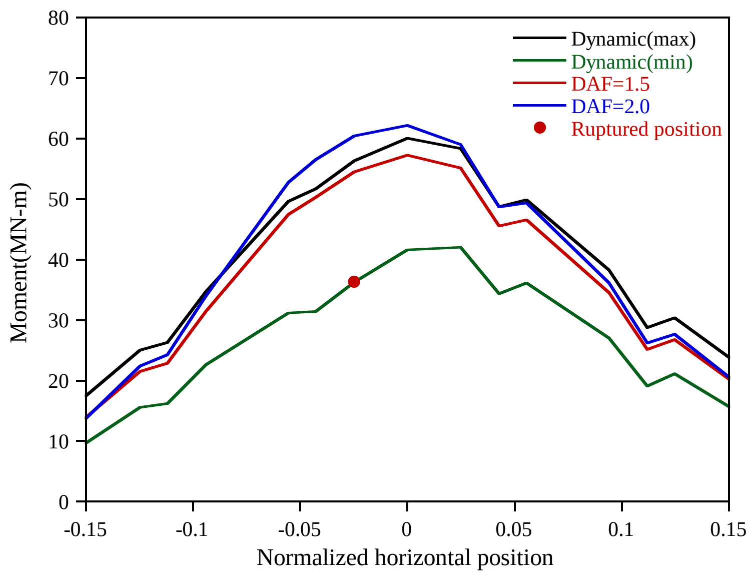


(b)

Fig. 3.10. Cable rupture located at one sixth point of 2nd Jindo bridge's main girder: (a) cable tension; (b) girder moment



(a)



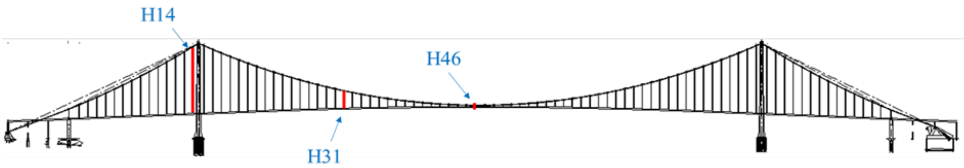
(b)

Fig. 3.11. Cable rupture located at a half point of 2nd Jindo bridge's main girder:

(a) cable tension; (b) girder moment

3.3. DAF for Suspension Bridge

Fig. 3.12 shows three suspension bridges which have different lengths of a main span: Yisunshin bridge which has a 1545m main span, Ulsan bridge which has a 1150m main span and New Millennium bridge which has a 650m main span. Three suspension bridges are used for examples to determine DAF. In three suspension bridge, the numbers of installed hangers are 87, 62 and 80 respectively. Fig. 3.12 also shows the ruptured hangers: the hanger near the pylon, the hanger located at a quarter point of the main span and the hanger located at a half point of the main span. Hangers are given the number from left to right to call each hanger



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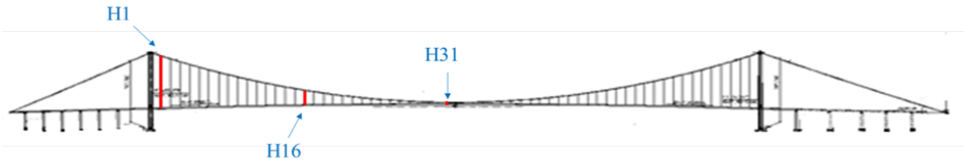


(b)

(c)

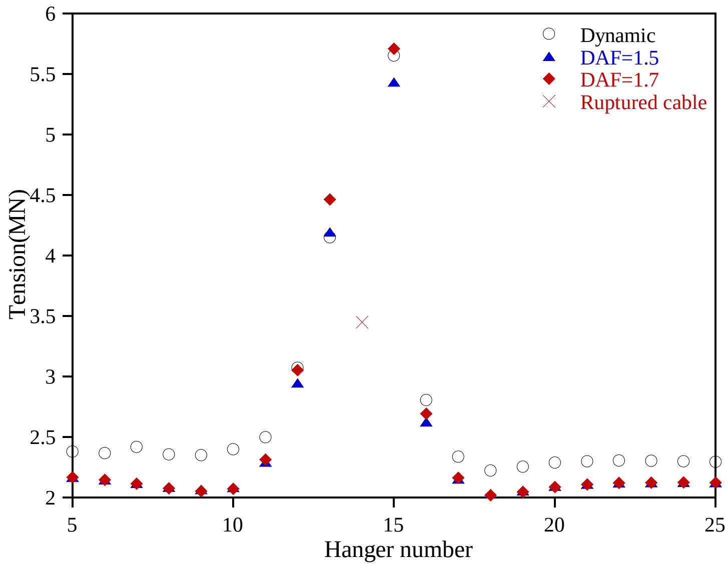
Fig. 3.12. Longitudinal section view and ruptured cables of suspension bridges:

(a) Yisunshin bridge; (b) Ulsan bridge; (c) New Millennium bridge

Fig. 3.13, Fig.3.14 and Fig. 3.15 show the results of quasi-static analysis and dynamic analysis as the hanger ruptures near the pylon, at a quarter point of the main span and at a half point of the main span respectively in Yisunshin bridge. When DAF is equal to 1.5, the error between the results of quasi-static analysis and that of dynamic analysis can be minimized in terms of hanger tension in Fig. 3.13(a), Fig. 3.14(a) and Fig. 3.15(a). Meanwhile, the responses of quasi-static analysis is greater than that of dynamic analysis with regard to girder moment in Fig. 3.13(b), Fig. 3.14(b) and Fig. 3.15(b). Because DAF should be decided conservatively, 1.5 is appropriate for the case of Yisunshin bridge as DAF.

Fig. 3.16, Fig.3.17 and Fig. 3.18 show the results of two analyses as the rupture occurs to the hanger at a point near the pylon, a quarter point of the main span and a half point of the main span respectively in Ulsan bridge. In Fig. 3.19, Fig.3.20 and Fig. 3.21, there are the results of two analyses as the hanger ruptures at a point near the pylon, a quarter point of the main span and a half point of the main span respectively in New Millennium bridge, too. Overall, the results of Ulsan bridge and New Millennium bridge have the similar tendency to the results of Yisunshin bridge. But the different tendency is discovered in the case that the cable located at a quarter point of the main span ruptures. In Fig. 3.17(a) and Fig. 3.20(a), the tension of quasi-static analysis applying 1.5 as DAF is smaller than the tension of dynamic analysis. As the results of quasi-static analysis should be more conservative than that of dynamic analysis, the tension of quasi-static analysis applying 1.7 is also included in Fig. 3.13(a) ~ Fig. 3.21(a).

If the overall error is considered, DAF might be determined as 1.5. However, quasi-static analysis is used for safety about cable rupture instead of dynamic analysis. Therefore, it is considerable to use 1.7 as DAF though there are a little conservative results.



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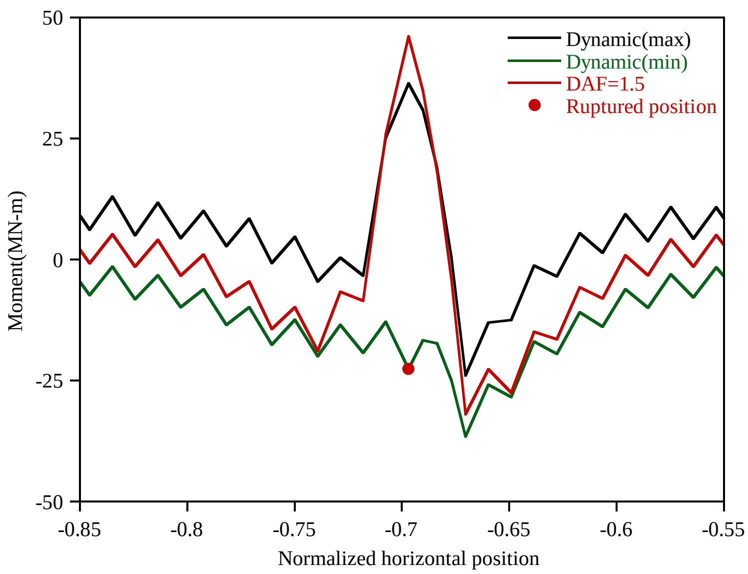
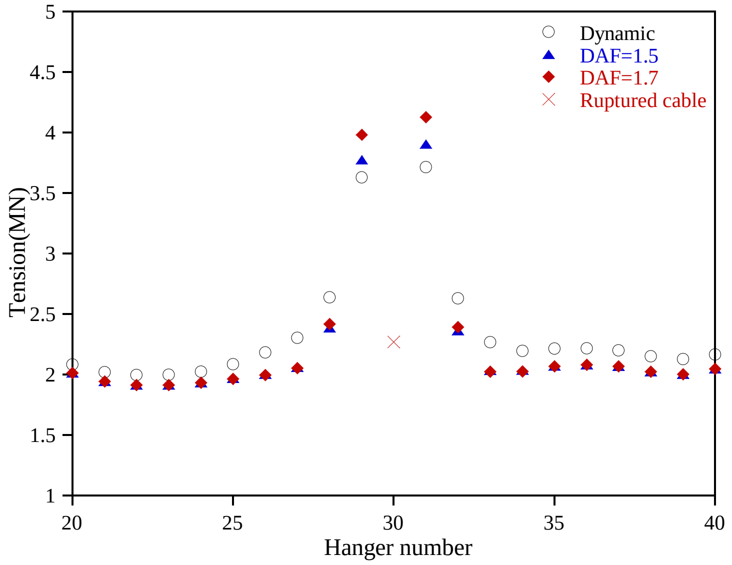


(b)

Fig. 3.13. Hanger rupture near the pylon of Yisunshin bridge's main girder:

(a) hanger tension; (b) girder moment



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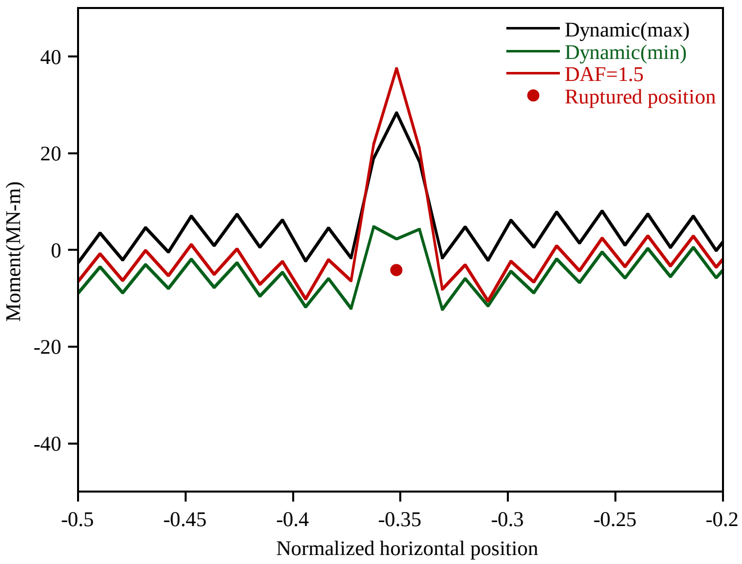

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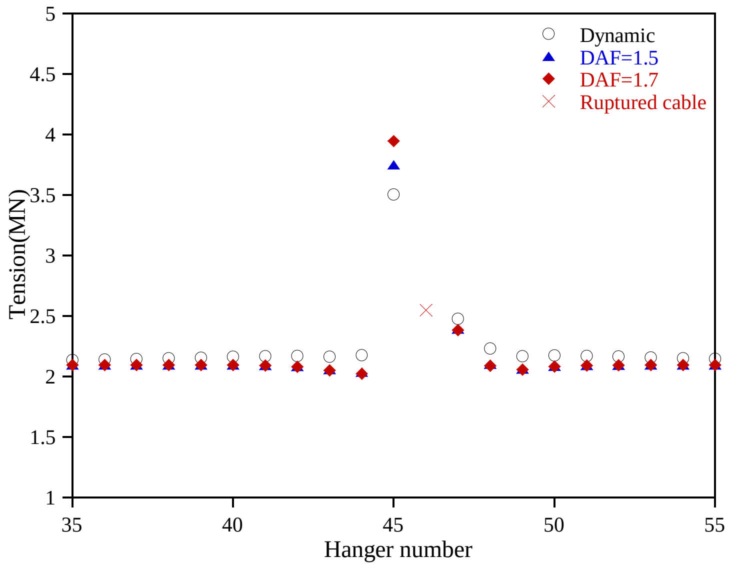
Fig. 3.14. Hanger rupture located at a quarter point of Yisunshin bridge's main girder: (a) hanger tension; (b) girder moment



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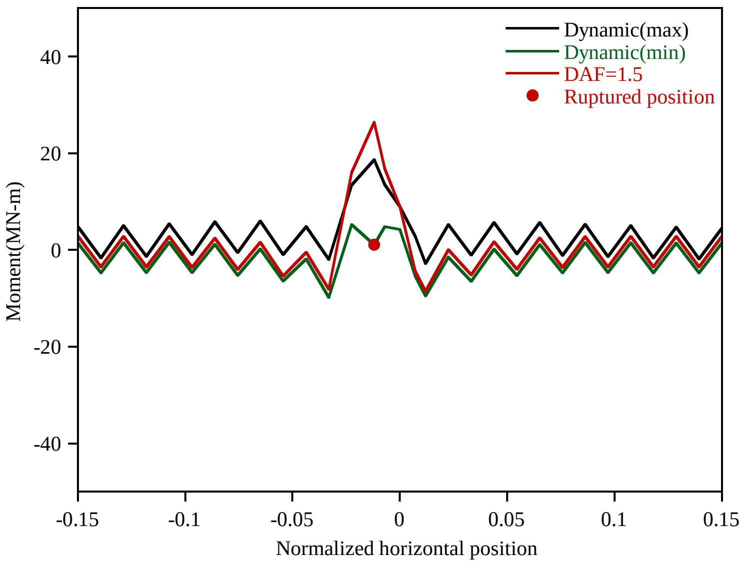
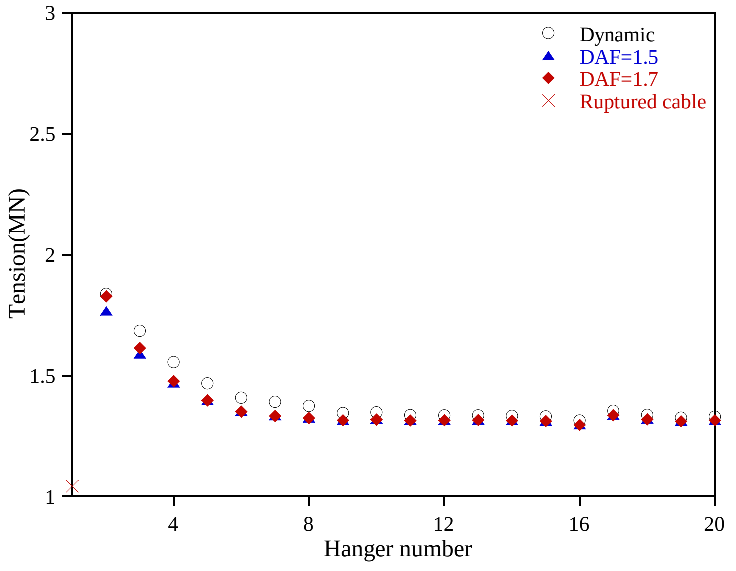


(b)

Fig. 3.15. Hanger rupture located at a half point of Yisunshin bridge's main girder:

(a) hanger tension; (b) girder moment



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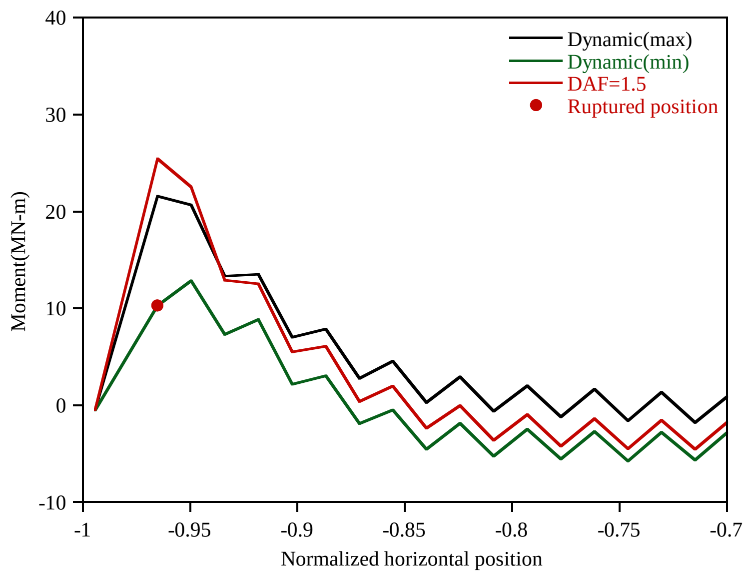
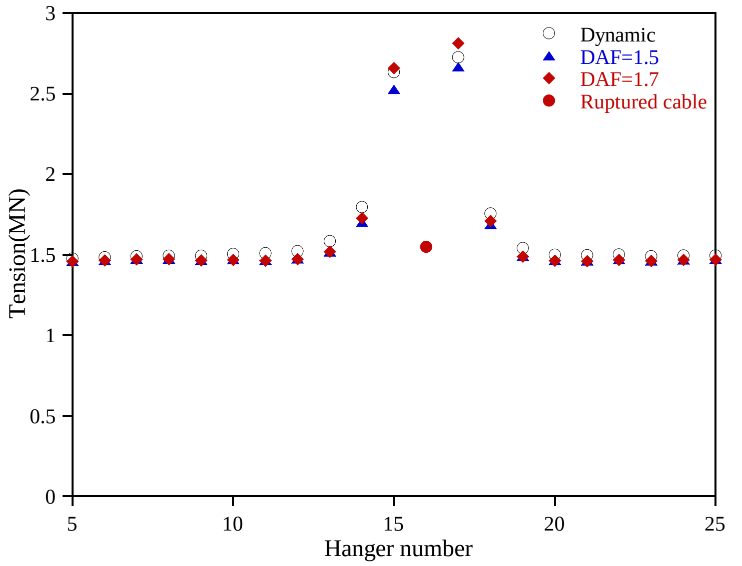


(b)

Fig. 3.16. Hanger rupture near the pylon of Ulsan bridge's main girder: (a) hanger tension; (b) girder moment



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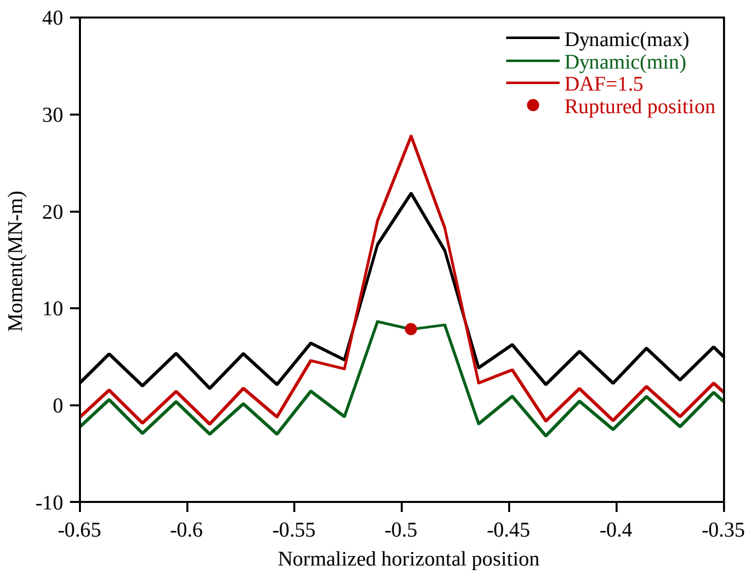

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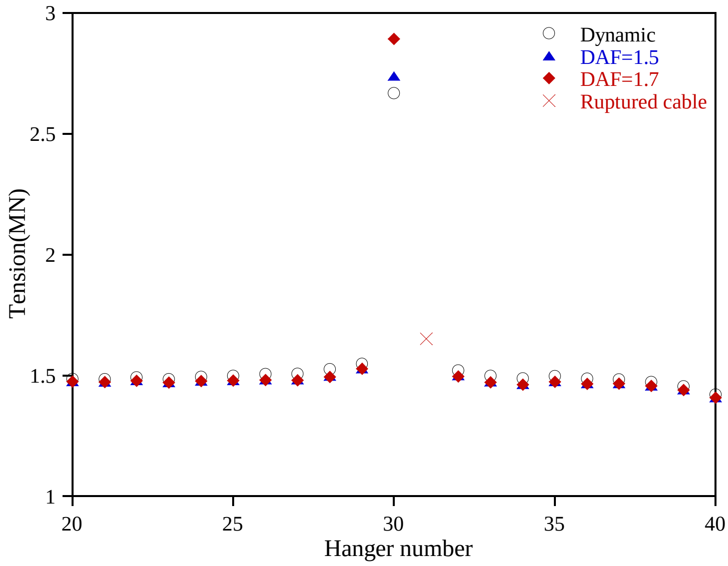
Fig. 3.17. Hanger rupture located at a quarter point of Ulsan bridge's main girder:

(a) hanger tension; (b) girder moment



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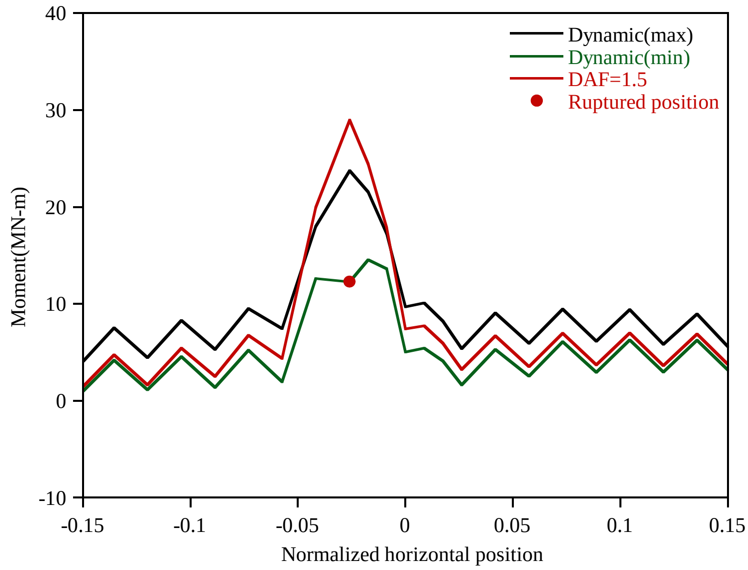
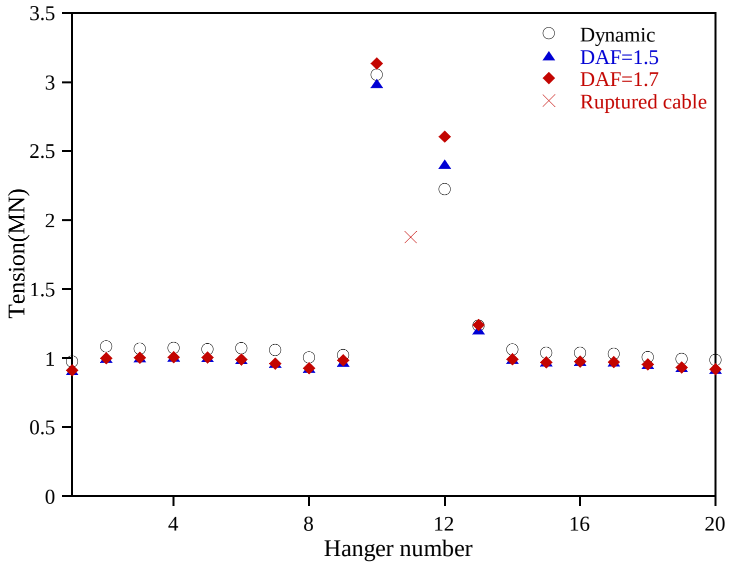


(b)

Fig. 3.18. Hanger rupture located at a half point of Ulsan bridge's main girder:

(a) hanger tension; (b) girder moment



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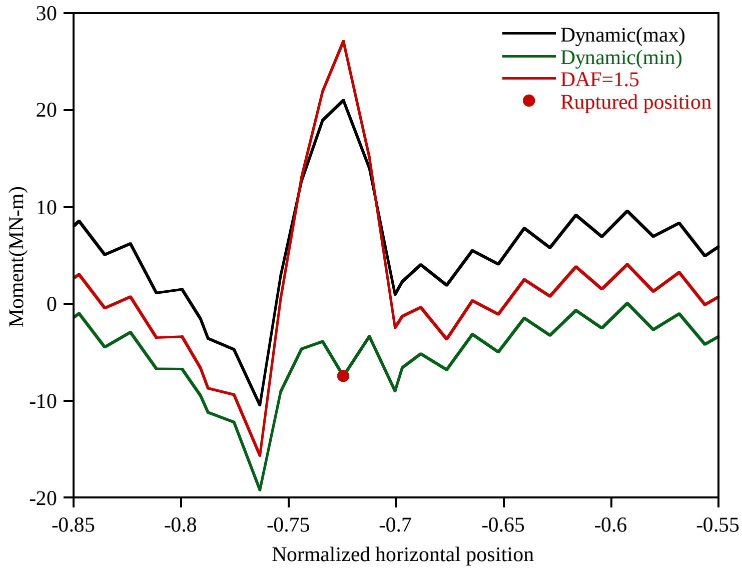
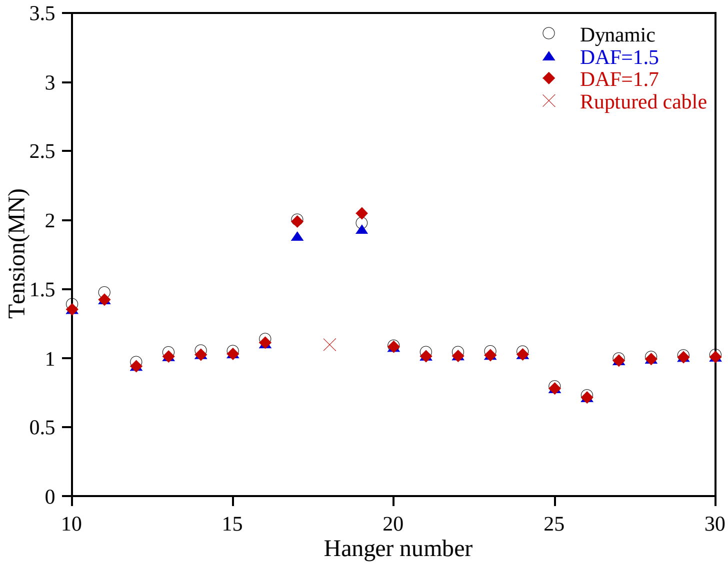


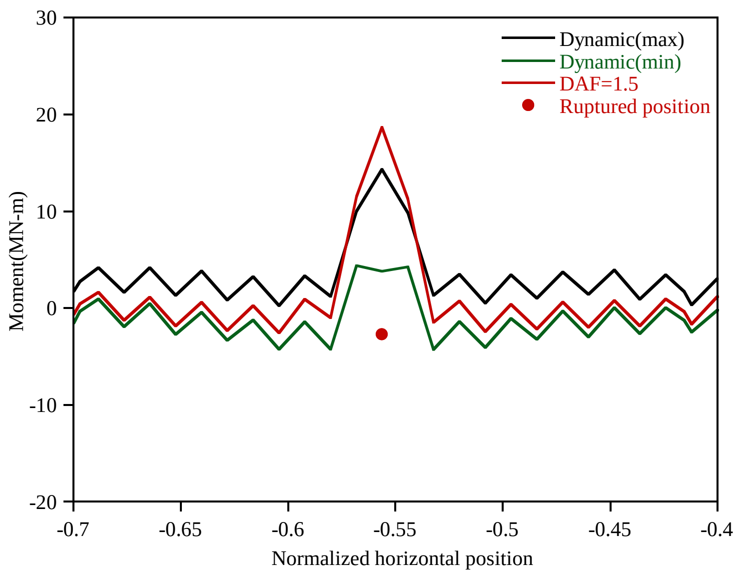
(b)

Fig. 3.19. Hanger rupture near the pylon of New Millennium bridge's main girder:

(a) hanger tension; (b) girder moment

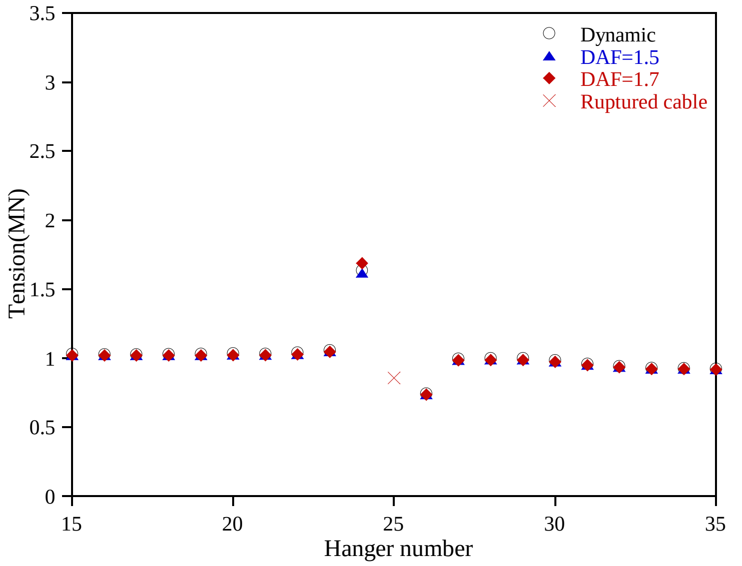


(a)

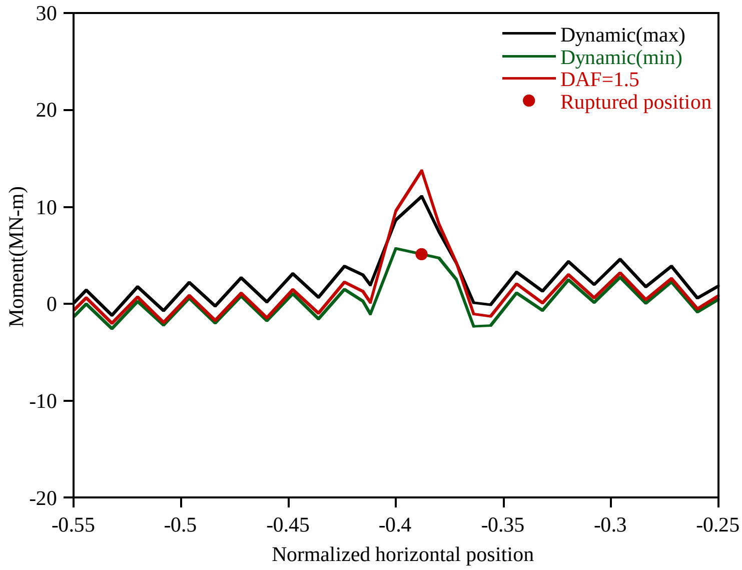


(b)

Fig. 3.20. Hanger rupture located at a quarter point of New Millennium bridge's main girder: (a) hanger tension; (b) girder moment



(a)



(b)

Fig. 3.21. Hanger rupture located at a half point of New Millennium bridge's main girder: (a) hanger tension; (b) girder moment

4. Reliability Assessment for Tension about Cable Rupture

The accidental cable rupture causes a huge dynamic effect and it may lead to the damage of other elements including the other cables. Consequently, the probability of a series of the cables rupture should be calculated as the reliability assessment is performed about the cable rupture. In this study, Advanced First Order Second Moment (AFOSM) method is used for the reliability assessment of the adjacent cables about the cable rupture.

4.1. Method of Reliability Assessment

The standard of the failure state is required to perform the reliability assessment. Limit state function is a function that defines the limit state and is defined as Eq. (4.1). When limit state function is equal to 0, it is called the limit state equation. If the limit state function is positive, it is on a safe condition. On the contrary, if the limit state function is negative, it is on a failure condition.

$$
\begin{aligned}
g(X) &> 0 \ : \ \text{Safe} \\
g(X) &= 0 \ : \ \text{Limit state} \\
g(X) &< 0 \ : \ \text{Failure}
\end{aligned}
\tag{4.1}
$$

The limit state function in this reliability assessment is as follows in Eq. (4.2).

$$g(X) = R_n - S \tag{4.2}$$

R_n and S are the resistance random variable and the load random variable respectively. In detail, R_n and S present the tensile strength of the cables and the load effects of ALS3 in the structure.

4.1.1. Resistance Random Variable

Because the safety factor is considered in the design of bridge, the tensile strength of the cables is designed conservatively in most cases. For that reason, it is expected that the reliability index for cable tension is a little high relatively. But this study intends to verify the safety for cable rupture when the optimal cross-section is designed in accordance with KHBDC(2015). Therefore, resistance strength can be calculated using Ultimate Limit States(ULS) 1 in Eq. (4.3). If resistance factor ϕ and resistance modification factor ϕ_{rm} is equal to 0.76 and 0.79 respectively, the nominal strength of cables targeting reliability index 5.6 can be calculated using Eq. (4.4). Required resistance strength is set to the nominal strength of cables and the cross-sectional area of cables decreases to satisfy the required resistance strength.

$$R_{req} = \gamma_p (DC + DW) + 1.8(LL + IM) \tag{4.3}$$

$$\phi_{rm} \phi R_n = R_{req} \tag{4.4}$$

If the cross-sectional area of cables declines maintaining the other elements identically, the tension of each cable and the initial configuration of bridge change. Simple Target Configurations Under Dead loads(TCUD) method is utilized to keep the tension and the initial configuration although the cross-sectional area changes(MOLIT 2016). Simple TCUD method is the method that the tension and the initial configuration are maintained by adjusting the unstrained length.

The type and distribution characteristic of cable resistance strength are as follows in Table 4.1. The type and distribution are taken from the reference of Lee (2014) and Lee et al. (2015).

Table 4.1. Resistance random variable distribution characteristic

Type	Bias Factor λ	C.O.V δ	Type of distribution	Reference
Tensile strength of cable	1.07	12%	Lognormal	Lee (2014) Lee et al. (2015)

4.1.2. Load Random Variable

Eq. (4.5) is load S using in the reliability assessment.

$$S = DC + DW + 0.75(LL + IM) + PS2 \tag{4.5}$$

where $PS2$ is the dynamic effect of cable rupture and quasi-static analysis applying DAF is used to describe $PS2$. DAF is equal to 1.5 in cable-stayed bridge and 1.7 in suspension bridge. Meanwhile, the live load factor 0.75 signifies a low probability of the concurrence of the maximum vehicular live load and the extreme events(KHBDC 2015).

Table 4.2 summarizes the type and distribution characteristic of load random variable. $DC1$, $DC2$ and $DC3$ are the load effect of factory-made elements, cast-in-place elements and cable elements; DW is the load effect of wearing surfaces and utilities; LL is the load effect of live load. DAF and $PS2$ are excluded from the list of random variable and are assumed as fixed values which do not have statistical characteristics.

Table 4.2. Load random variable distribution characteristic

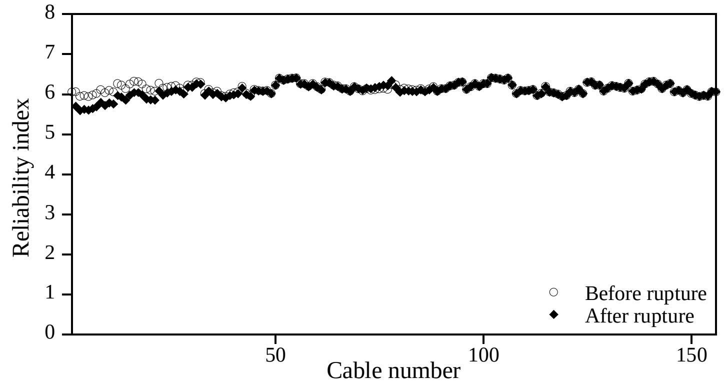
Type	Bias Factor λ	C.O.V δ	Type of distribution	Reference
$DC1$	1.03	8%	Normal	Nowak (1999)
$DC2$	1.05	10%	Normal	Nowak (1999)
$DC3$	1.00	6%	Normal	Lee (2014)
DW	1.00	25%	Normal	Nowak (1999)
LL	1.00	20%	Lognormal	Hwang (2008) Hwang et al. (2014)

4.2. Results of Reliability Assessment for Cable-Stayed Bridge

Similar to the determination of DAF, various cases of cable-stayed bridges should be needed to perform reliability assessment. Moreover, the ruptured cables are selected identically with the determination of DAF to maintain the consistency.

The reliability assessments are performed as the rupture of cable occurs at the outermost, one sixth point of the main span and a half point of the main span respectively for prototype cable-stayed bridge, shown in Fig. 4.1. The reliability indexes of cables are distributed near 6.0 before the rupture. Whereas the reliability indexes after the rupture are lower than the reliability indexes before the rupture in the adjacent area with the ruptured cable. The reliability index of the adjacent cable changes from 6.06 to 5.70 when the cable rupture at the outermost; from 6.22 to 5.27 when the cable rupture at one sixth point of the main span; from 6.12 to 5.61 when the cable rupture at a half point of the main span. In the second case of prototype cable-stayed bridge, the reliability index of the nearby cable is the lowest after rupture and the difference between the reliability indexes before and after the rupture is the greatest among the three cases.

The reliability index before the rupture is compared with the reliability index after the rupture for Incheon bridge shown in Fig. 4.2; for 2nd Jindo bridge shown in Fig. 4.3. In the cases of Incheon bridge, the reliability index decreases from 6.60 to 5.20 when the cable ruptures located at one sixth point of the main span. The tendency in Incheon bridge is similar to the tendency in prototype cable-stayed bridge. In the case of the cable rupture located at one sixth point of the main span, the reliability index of the adjoining cable is the lowest after rupture and the reliability index declines to the greatest width among the three cases, too. In 2nd Jindo bridge, the reliability index is modified from 6.55 to 5.39 in the case of the outermost; from 7.31 to 6.09 in the case of one sixth point of the main span; from 6.66 to 5.67 in the case of a half point main span. Because the reliability index before rupture is high relatively in the case of one sixth point of the main span, the case that the reliability index of adjoining cable is lowest is not the case of one sixth point of the main span but the case of the outermost. Nevertheless, the tendency that the reliability index decreases to the greatest width is identical to the tendency of the other cable-stayed bridges. In conclusion, the other cables can be damaged when the cable located at one sixth point of the main span ruptures, so that it is considered in the design of cables.



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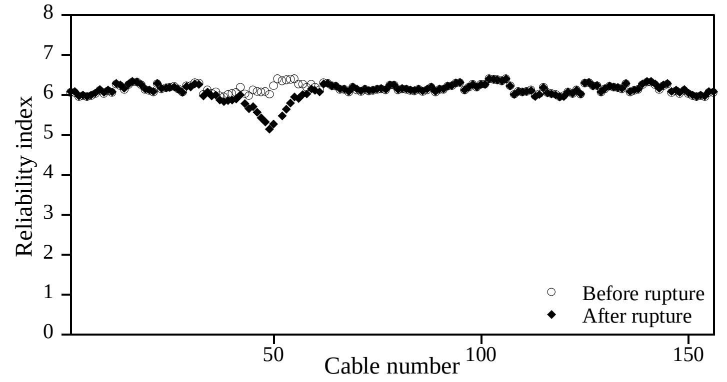

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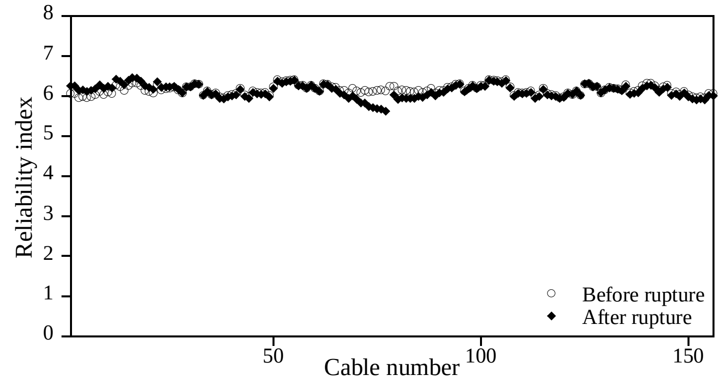
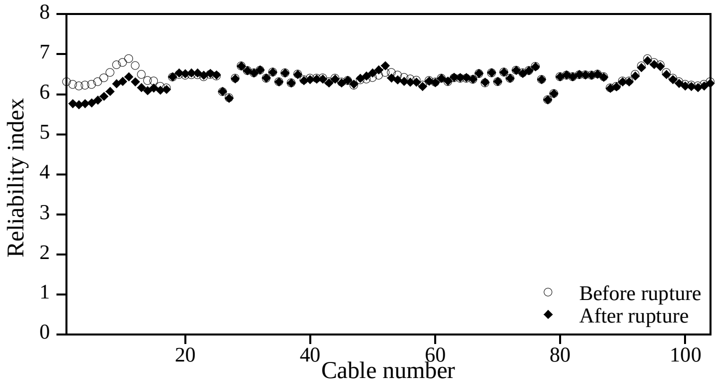


(c)

Fig. 4.1. Reliability index for prototype cable-stayed bridge: (a) cable at the outer-most point of the main girder; (b) cable at one sixth point of the main girder; (c) cable at a half point of the main girder



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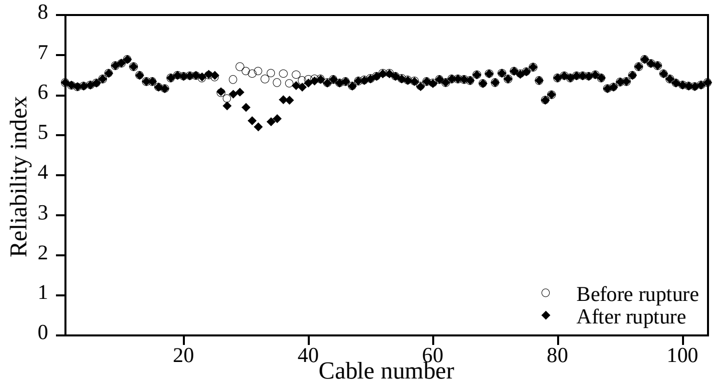

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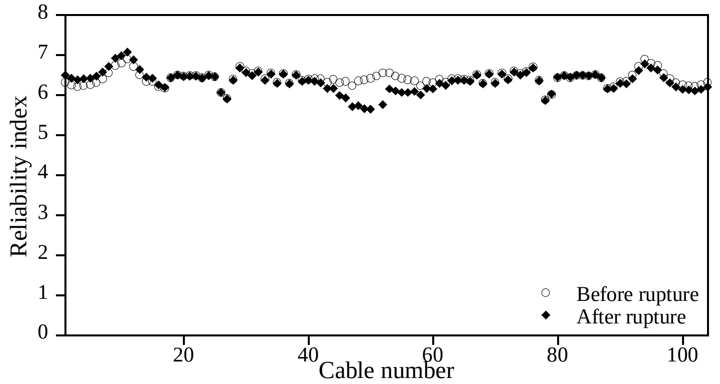
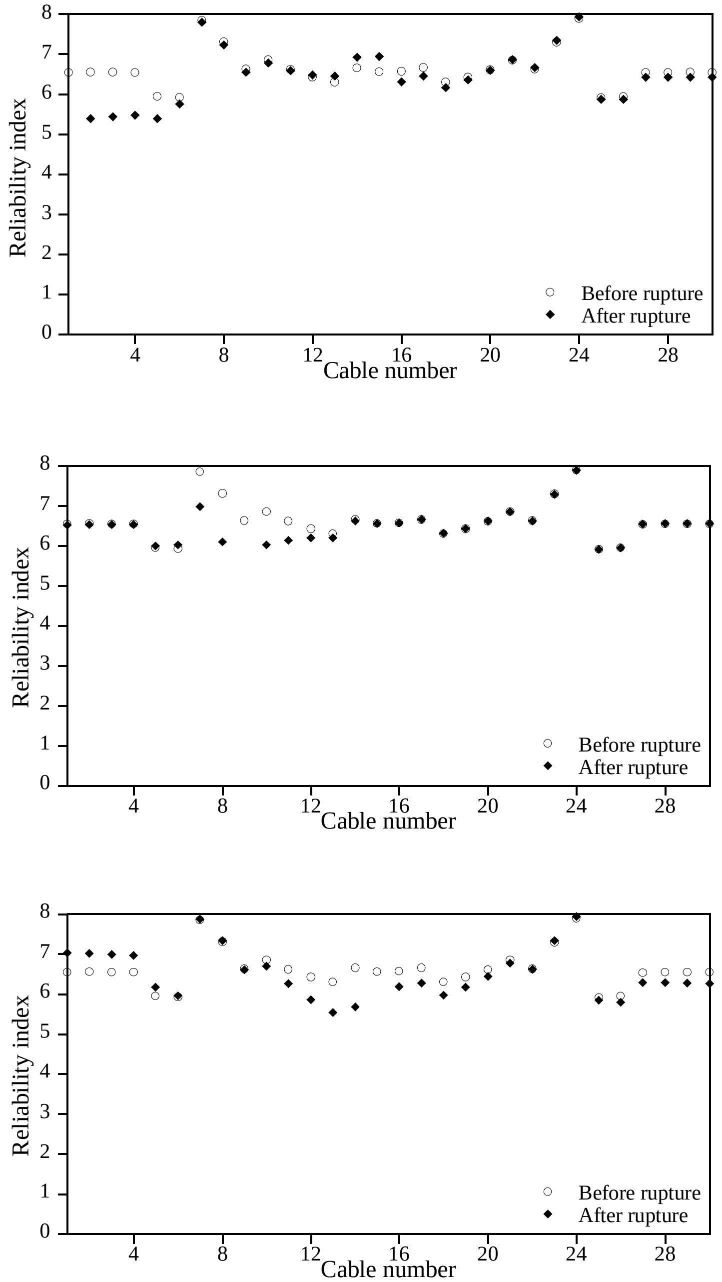


(c)

Fig. 4.2. Reliability index for Incheon bridge: (a) cable at the outermost point of the main girder; (b) cable at one sixth point of the main girder; (c) cable at a half point of the main girder



(a)

(b)

(c)

Fig. 4.3. Reliability index for 2nd Jindo bridge: (a) cable at the outermost point of the main girder; (b) cable at one sixth point of the main girder; (c) cable at a half point of the main girder

4.3. Results of Reliability Assessment for Suspension Bridge

The hanger near the pylon, the hanger located at a quarter point of the main span and the hanger located at a half point of the main span are selected as the ruptured hanger in the Yisunshin bridge, Ulsan bridge and New Millennium bridge for the reliability assessment similar to the determination of DAF.

Fig. 4.4 shows the results of reliability assessment before and after the rupture of the hanger for Yisunshin bridge. Before the rupture happens, the reliability indexes about the tension of the hanger are distributed to almost 6.0 similar to the cases of cable-stayed bridges. After the rupture happens, the reliability indexes of the adjacent hangers decrease to nearly 2.0 sharply in all cases. The results of reliability assessment before and after the rupture of the hanger for Ulsan bridge and New Millennium bridge are shown in Fig. 4.5 and Fig. 4.6 respectively. A sharp decline in the reliability index of the adjoining cables happens from nearly 6.0 to nearly 2.0 likewise.

Fig. 4.7(a) and Fig. 4.7(b) shows the tension of static analysis before the rupture of the cable and the maximum tension of dynamic analysis after the rupture in prototype cable-stayed bridge and in Yisunshin bridge, which are the longest cable-stayed bridge and suspension bridge in this study respectively. When the cable of prototype cable-stayed bridge ruptures, the tension of almost 20 cables increases by 10%. However, when the hanger of Yisunshin bridge ruptures, the tension of just 4 cables increases by 20%~80% sharply. For such a reason, it is considered that the reliability indexes in the cases of suspension bridges decrease more than the reliability indexes in the cases of cable-stayed bridges.

When the hanger near the pylon in New Millennium bridge ruptures, the reliability index of the adjacent hanger decreases to 0.27 shown in Fig. 4.6(a). This result is the steepest drop among the other cases. It is designed that the cross-sectional area of the hanger near the pylon is about two times that of the other hangers. When the hanger which has the huge tension ruptures, the safety of the hanger which has the small tension is checked in this case. As a result, probability of cable rupture occurs greatly and the reliability index is smaller than any other cases. If there is the great difference of cross-sectional areas between the adjacent cables, it is reasonably considered in terms of the effects of the cable rupture that the small cross-sectional area needs to increase.

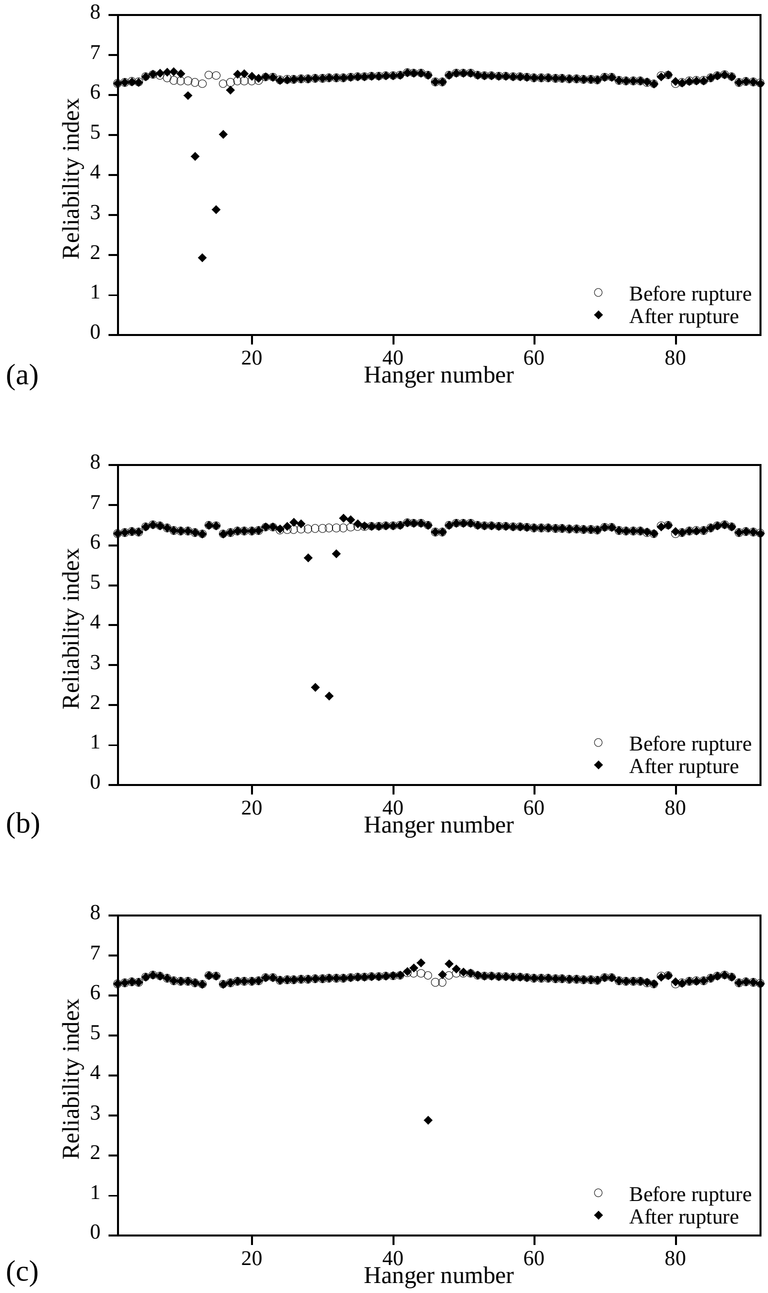


Fig. 4.4. Reliability index for Yisunshin bridge: (a) hanger near the pylon; (b) hanger at a quarter point of the main girder; (c) hanger at a half point of the main girder

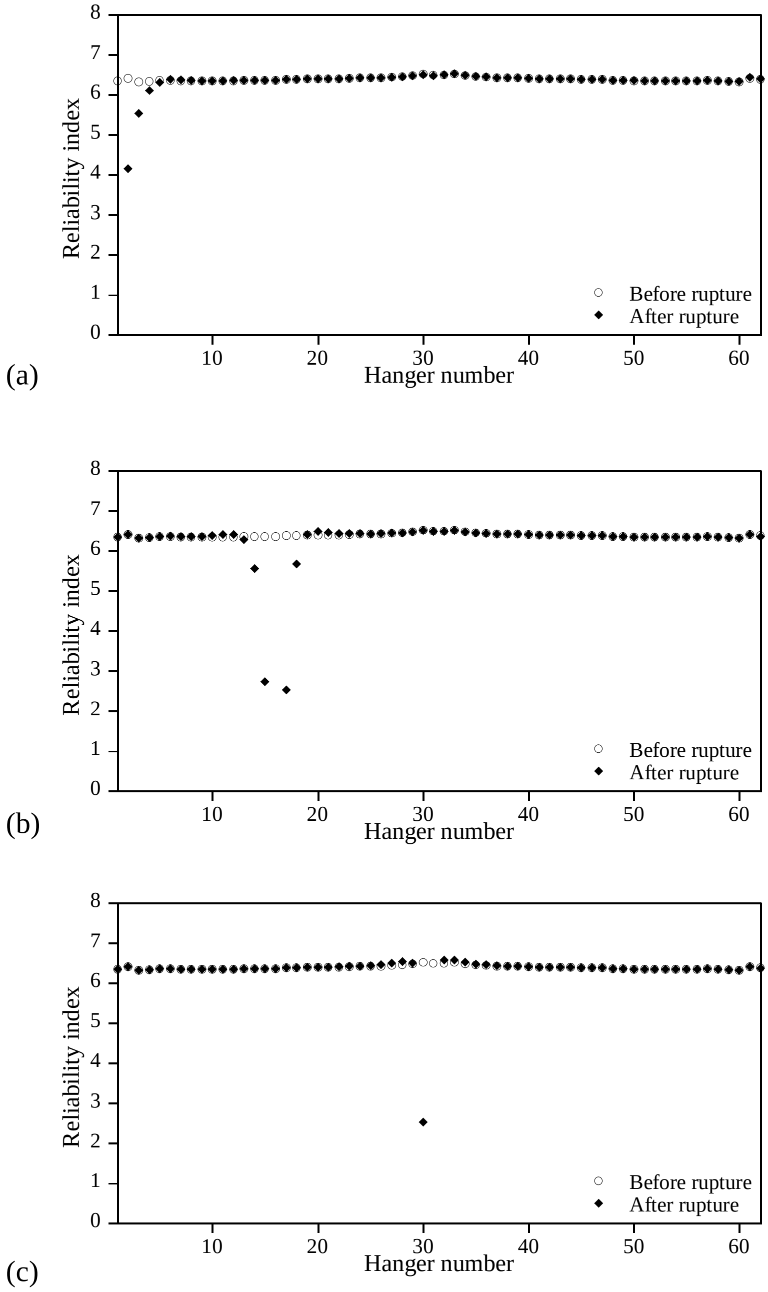


Fig. 4.5. Reliability index for Ulsan bridge: (a) hanger near the pylon; (b) hanger at a quarter point of the main girder; (c) hanger at a half point of the main girder

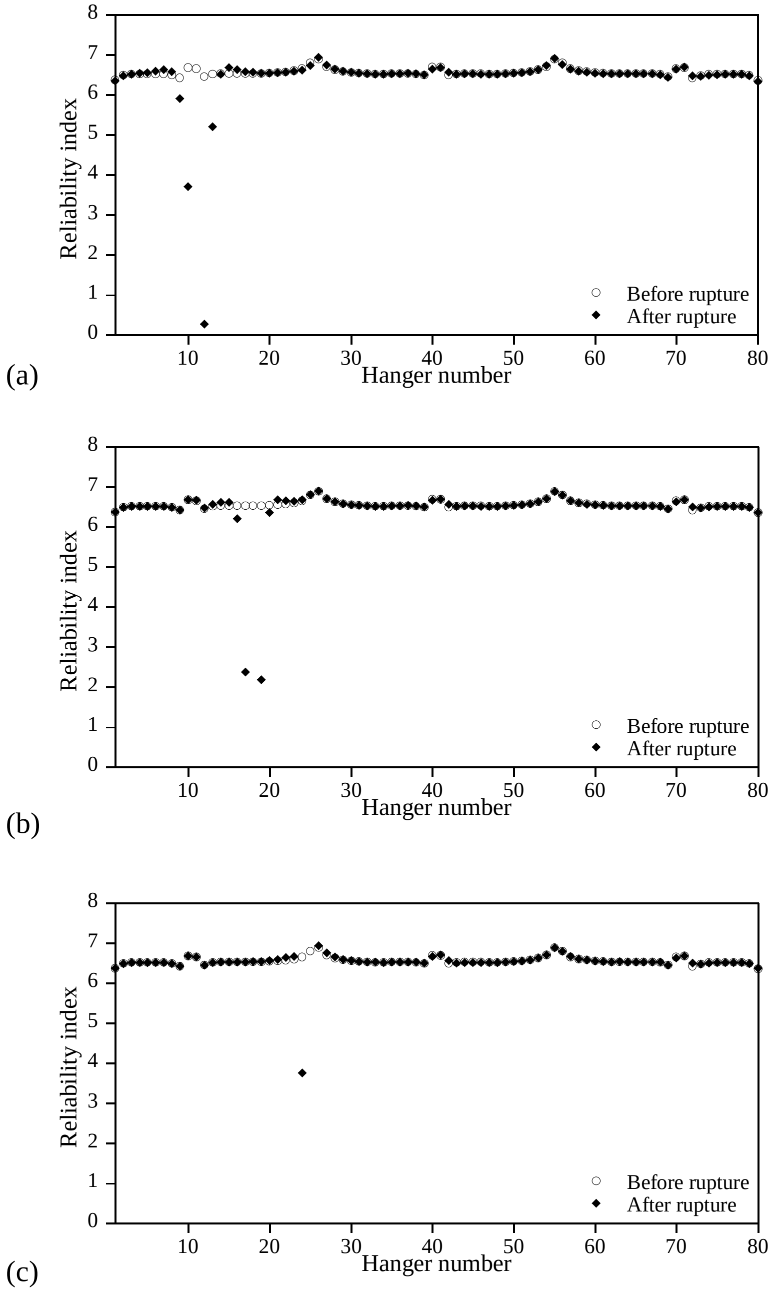
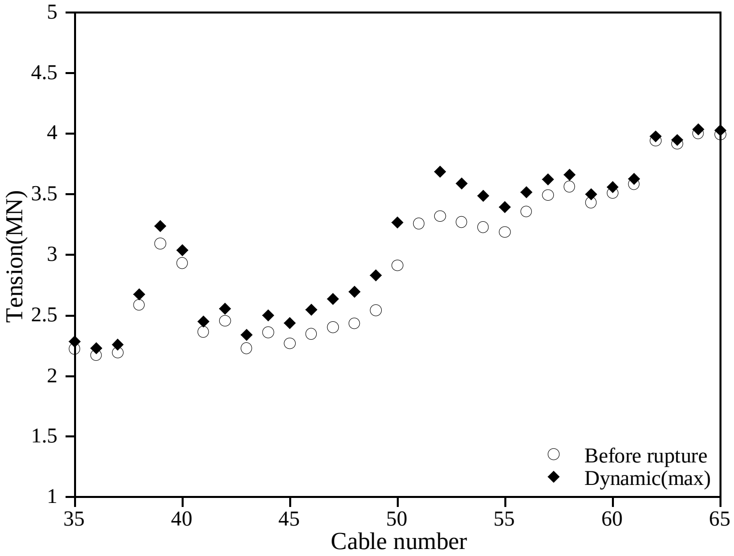


Fig. 4.6. Reliability index for New Millennium bridge: (a) hanger near the pylon; (b) hanger at a quarter point of the main girder; (c) hanger at a half point of the main girder



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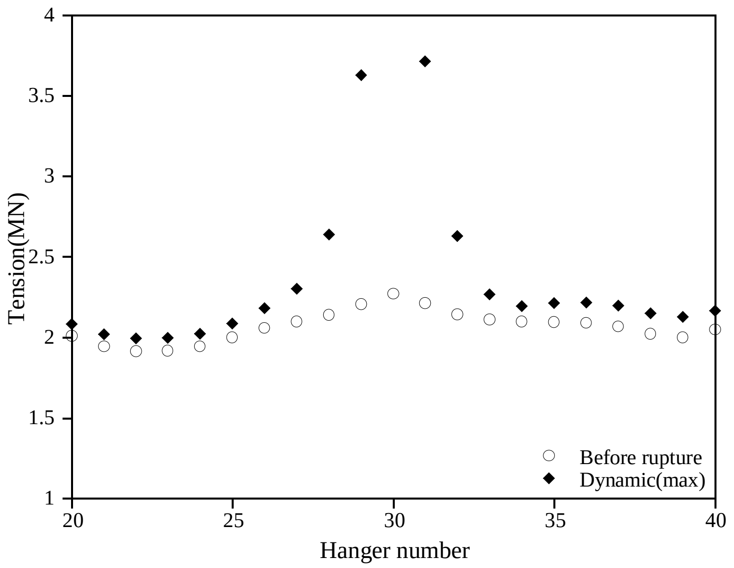

(b)

Fig. 4.7. Tension of the adjacent cable before and after rupture:

(a) prototype cable-stayed bridge; (b) Yisunshin bridge

5. Summary and Conclusions

There are two methods to confirm the safety of the cables when the cable ruptures abruptly: Quasi-static analysis applying for DAF and Dynamic analysis. In this study, DAF is determined for quasi-static analysis to describe dynamic analysis correctly. In addition, the reliability assessment is performed to check that the load combination and method contained in KHBDC(2015) could guarantee the safety of the cable elements.

Quasi-static analysis and dynamic analysis are performed and DAF is decided when there is the minimum error between the result of quasi-static analysis and that of dynamic analysis. The tension of cable and the moment of girder are used as the results of quasi-static analysis. The maximum tension of cable and the maximum and minimum moment of girder are also selected as the results of dynamic analysis. The range of this study is limited to the section which are close to the ruptured cable.

In the cable-stayed bridge, the cables located at the outermost, one sixth point of the main girder and a half point of the main girder in prototype cable-stayed bridge, Incheon bridge and 2nd Jindo bridge are chosen as the ruptured cable. There are the small differences depending on size and location, but it is considerable to use 1.5 as DAF for the cable-stayed bridge.

In the suspension bridge, the analyses are performed when the cable located near the pylon, at a quarter point of the main girder and at a half point of the main girder ruptures for Yisunshin bridge, Ulsan bridge and New Millennium bridge. 1.5 is suitable for DAF in most cases of suspension bridge, but 1.7 is the suitable value as DAF for the tension of the cable in a quarter of the main girder for Ulsan bridge and New Millennium bridge. The results of quasi-static analysis should be more conservative than that of dynamic analysis. As a result, it is considerable to use 1.7 as DAF for the suspension bridge.

AFOSM is used for the reliability assessment of the adjacent cables when the cable ruptures. The location and type of bridges used in the reliability assessment are identical with the cases of the determination of DAF and the cross section is re-designed according to KHBDC(2015) using the simple TCUD.

When the ruptured cable occurs in the cable-stayed bridge, the reliability indexes of the adjoining cables are distributed from 5.20 to 6.09. When the cable located at one sixth point of the main girder in the three cable-stayed bridges ruptures, the reliability indexes of the adjoining cables decrease highly. As a result, the cable located at one sixth point of the main girder might be important for the design of the cables.

When the ruptured cable occurs in the suspension bridge, the reliability indexes of the adjacent cables are spread from 0.27 to 4.15. The difference of indexes between before and after rupture in the suspension bridge is greater than that in the cable-stayed bridge. When the hanger ruptures in the suspension bridge in comparison with the cable-stayed bridge, the dynamic impacts affect the adjacent cables greatly. The low index, 0.27, is resulted in the case that the cable located near the pylon ruptures because there is a great gap between the cross-sectional areas of the two adjacent cables. As a result, if the gap between the cross-sectional areas of the two adjacent cables is large, it is reasonable that the small cross-sectional area needs to increase.

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초 록

본 연구는 케이블 파단에 대한 안전성 검토를 위하여 준정적 해석 결과가 동적 해석 결과를 잘 묘사하도록 동적증폭계수를 산정하고, 케이블 파단이 발생하였을 때 인접 케이블의 안전성을 확인한다. 국내외 주요 설계기준에서 케이블 파단에 대한 검토 방법은 동적증폭계수를 적용한 준정적 해석, 동적 해석 2 가지 방법이 존재한다. 준정적 해석으로 상대적으로 정확한 방법인 동적 해석을 잘 묘사하기 위해서는 정확한 동적증폭계수를 사용하는 것이 중요하다. 본 연구에서는 동적증폭계수 용어 자체의 의미보다는 두 가지 해석 결과의 유사성에 초점을 두고 진행한다. 먼저 동적 해석 결과를 비교 기준으로 설정하고, 동적증폭계수를 조절해가며 준정적 해석을 실시하여 결과를 비교한다. 사장교에서는 경간 길이가 각각 다른 프로토타입 사장교, 인천대교, 제 2 진도대교에 대하여, 현수교에서는 이순신대교, 울산대교, 새천년대교에 대하여 두 가지 해석을 실시하고 파단 인접 구간의 케이블 장력, 거더 모멘트를 기준으로 비교하여 오차를 가장 작게 발생시키는 동적증폭계수를 산정한다. 추가적으로 케이블 파단이 발생하였을 때 다른 케이블의 장력에 대한 신뢰도 평가를 실시한다. 케이블 장력에 대한 신뢰도 평가를 실시할 때도 다양한 경간 길이에 대한 교량의 안전성을 확인하기 위하여 동적증폭계수 산정에 사용된 예제를 동일하게 사용한다. 도로교설계기준(한계상태설계법)-케이블교량편(2015)에 대한 최적 설계를 할 수 있도록 간이 TCUD 를 사용하여 케이블 단면적을 감소시킨 후, 케이블 장력에 대한 신뢰도 평가를 실시한다.

주요어: 동적증폭계수, 준정적 해석, 동적 해석, 신뢰도 평가, 케이블 파단, 한계상태설계법

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