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CONSTRUCTION OPERATIONS SIMULATION UNDER STRUCTURAL ADEQUACY CONSTRAINTS: THE STONECUTTERS BRIDGE CASE STUDY

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ABSTRACT

The progress on a bridge construction project is inevitably dictated by construction sequence, resource availability and structural adequacy. Most construction planning exercises consider only time, sequence and resource factors. However, in practice, the structural adequacy of a partially formed permanent bridge along with critical temporary facilities is heavily weighted by site engineers, as different construction strategies not only affect the sequencing of activities and allocation of resources, but also result in changes in requirements for temporary structural supports and in loading performances of permanent structures. An integrated bridge planning approach examines different construction strategies through both the operations management perspective and the structural integrity perspective. To demonstrate the necessity and feasibility of such an integrated analysis method, planning of the Stonecutters Bridge in Hong Kong was investigated as a case study. The integrated analysis method was applied to the typical bridge segment erection cycle and the results and findings are reported in the paper.

1 INTRODUCTION

Construction operations simulation research focuses on detailed construction operations, based on computer simulation technology, thereby improving the construction productivity and utilization of resources and constructing projects economically. The research in this domain has gained momentum in the last few decades, but most research has focused on simulation engine development, visualization and animation of construction operation simulation. For instance, several simulation engines have been developed, such as CYCLONE (Halpin 1977), Micro-CYCLONE (Halpin 1989), Dynamic Interface for Simulation of Construction Operation (DISCO) by Huang and Halpin in 1993, Simphony (AbouRizk and Hajjar 1998), STROBOSCOPE (Martinez and Ioannou 1999), and SDESA (Lu 2003). However, most research focuses only on time, sequence and resource factors in construction planning, and the structural adequacy did not draw much attention. The progress on a construction project, especially a bridge project, is inevitably dictated by construction sequence, resource availability and structural adequacy. Some research was dedicated to structural analysis in different stages of construction, like the study on pylon and beam synchronous construction of cable-stayed bridge by Xu et al. (2007). Nevertheless, the operations management perspective is usually overlooked in analysis of structure oriented research.

In view of the practical need for concurrent consideration of both time/cost and structural integrity, this research proposed an integrated simulation method and applied it in a cable-stayed bridge construction project. The integration of the operations simulation and structure analysis modeling technology

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adopted in this research is both robust and well developed. SDESA (Lu 2003) is employed for operations simulation while structure analysis is performed by a professional bridge modeling program – MIDAS.

In the following, the project background, typical bridge construction operations, and how the proposed integrated simulation was applied in the project are illustrated. The case study results and observations demonstrated the proposed method assisted engineering practitioners to plan and schedule their work in a more comprehensive view, which is difficult to achieve with ordinary construction planning tools or structure analysis packages alone.

2 PROJECT BACKGROUND

The Stonecutters Bridge is a 1,596 m (meter) long, dual 3-lane, high level cable stayed bridge, with a clear span of 1,018 m. The bridge straddles the Rambler Channel at the entrance to the busy Kwai Chung Container port in Hong Kong. With a highly distinctive form, its key design features include a 1,018 m long steel main span supported by two 290 m tall concrete and stainless steel towers, and the slim steel deck splits into two streamlined boxes connected by cross girders.

The Stonecutters Bridge is formed by two concrete pylons (i.e. towers) and two concrete spans supported by four piers at each side standing on the back-up land (i.e. backspan). The steel deck (i.e. midspan) of the bridge is connected to the concrete spans at each side and is hanged by the cables. Cables are anchored to the midspan while the load taken by the towers is balanced by the self weight of the backspan via another set of cables anchored to the backspan from the towers (Figure 2). The bridge deck is in a twin box structure form and prefabricated in segments. Each segment is hanged by a pair of cables (each cable anchored at the outside edge of the twin boxes). In total, there are 65 steel deck segments and 112 cables. The typical width of each steel deck segment is 53 m while the length is about 18 m (Figure 3).

Figure 1: Stonecutters Bridge under construction

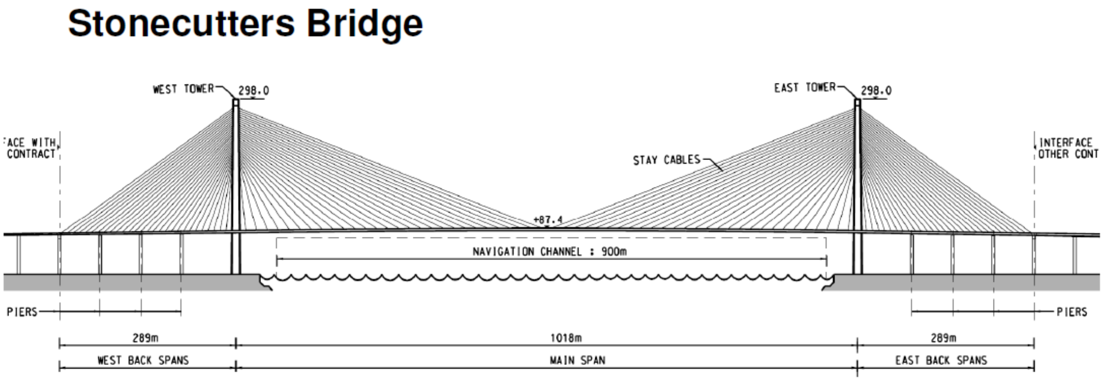


Figure 2: Side view of Stonecutter Bridge showing the skeleton of its structure

Figure 3: Typical steel deck segment of the bridge

3 TYPICAL CONSTRUCTION CYCLE OF THE BRIDGE

After completion of the backspan structure and other associated stitching works between the concrete structure and steel structure, the steel deck erection and cable installation came to the typical repetitive cycle. The typical cycle started from the arrival of the prefabricated segment. The lifting gantry, which was situated on the last erected segment, hooked up the segment from a transportation barge. The segment was lifted to deck level and secured to a temporary support frame as temporary fixing. The segment was then aligned, leveled and strand jacked horizontally into its correct position. It was then welded to the preceding segment. After that, the stay cables were installed to the segment. Cable unreeled from cable coil was first anchored to the tower and the deck. After the anchorage work was completed, the cable was stressed by a heavy jack until the designed length was reached. To balance the bending acting on the tower, one backspan cable and one midspan cable had to be stressed in each typical construction cycle. The typical erection cycle was repeated until the last closure segment, which would be operated in distinct method.

4 SIMULATION OF THE TYPICAL SEGMENT ERECTION SEQUENCE BY SDESA

The abovementioned typical repetitive operations are highly suitable for analysis via operations simulation. In this study, the original typical construction cycle (original case) was first fit into the proposed integrated simulation method, and to highlight the practical value of the method, a modified construction cycle (alternative) was also developed and put into comparison in terms of both their operations efficiency and structural adequacy.

The original typical construction cycle follows the steps as shown in Figure 4A. The cyclical process starts from (1) one backspan cable is installed, then (2) the segment is lifted up and welded, then (3) one midspan cable is installed, then (4) lifting gear advances to the next segment, then goes back to step (1) for the next cycle.

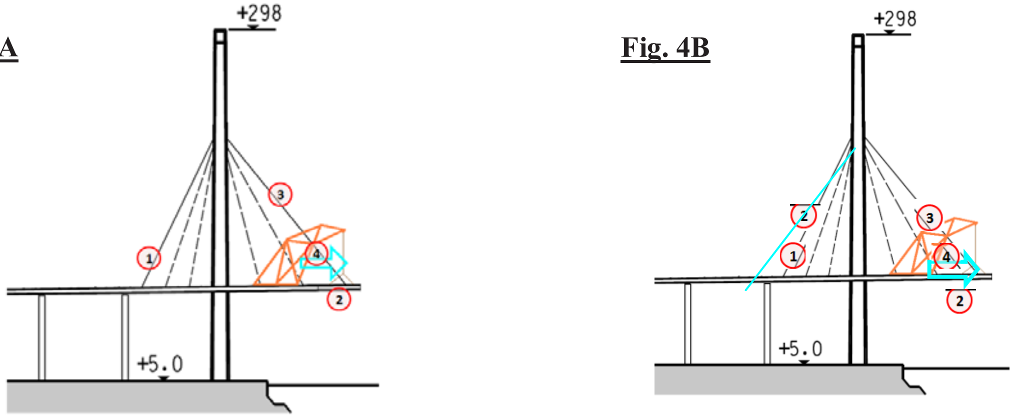


Figure 4: Illustration of the original segment erection cycle and its alternative

The original typical segment erection cycle was converted into an SDESA model (Figure 5), in which there were 3 work flows: (1) installation of backspan cable, (2) erection of steel deck segment, and (3) installation of midspan cable. The model starts with the activity “Lifting to Tower Anchorage (B)” (where the (B) stands for “Backspan”). The starting activity is the unreeling of cable, in which the tower crane hooks up the cable to the tower anchorage point with the assistance of a 360 ton mobile crane. Once the cable is anchored to the tower, the 360 ton mobile crane pulls another end of the cable for the deck anchorage at the backspan (i.e. activity “Anchor to Deck (B)”). Then the cable is stressed to the designed length and locked in the deck anchorage tube (i.e. activity “Stress Cable (B)”). After the backspan cable is stressed, the segment lifting activity (i.e. activity “Liftup Segment”) starts. This activity is triggered by the generation of the disposable resources (i.e BACK_OK) at the end of activity “Stress Cable (B).” The segment undergoes welding (i.e. activity “Weld Segment”) once it is lifted to the deck level. Once the welding is completed, the midspan cable is unreeled (i.e. activity “Lifting to Tower Anchorage (M)”, where (M) stands for Midspan) and plugged to the deck anchorage tube (i.e. activity “Anchor to Deck (M)”) and stressed to the designed length (i.e. activity “Stress Cable (M)”). The Lifting Gear (LG) then advances to the next segment (i.e. activity “Launch Lifting Gear to Next Segment”) when the stressing of the midspan cable is completed.

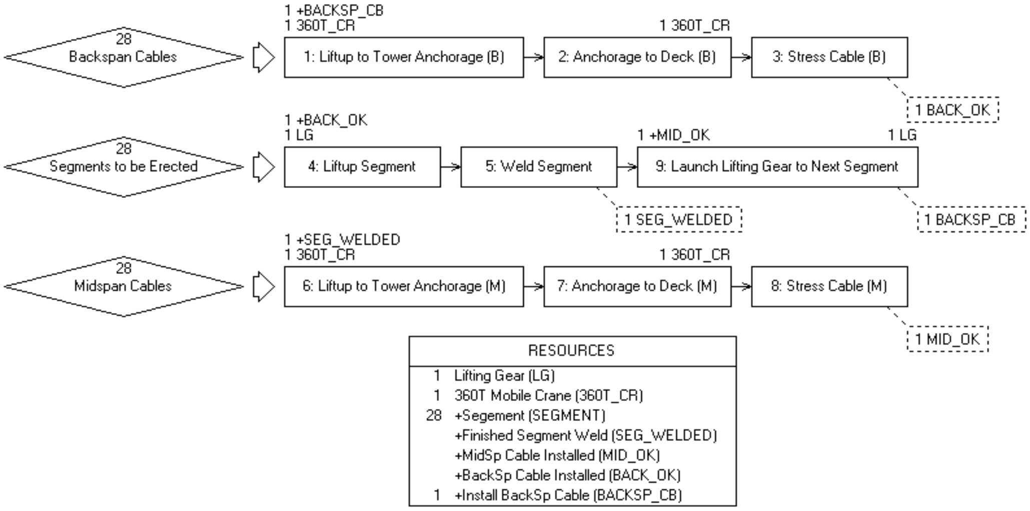


Figure 5: SDESA model of the base case typical segment erection work cycle

The activity time and resource transit time were collected based on the contractor's method statement, and entered into the SDESA model. All activities take 1 day constant duration to complete, except the weld segment activity which requires 4 days. The 360 ton mobile crane needs 0.2 days to transit between cable stress locations and cable unreel locations. This value is estimated based on site observations and it has some minor variation due to site condition and the increment distance between the backspan cable stressing location and the mainspan cable unreeling area with the increment of cantilever length. However, as the variation in the transit time is insignificant, the transit duration of the crane was also assumed constant.

The original segment erection cycle is modified slightly to set up an alternative work cycle. In the alternative operation mode, the installation of the next backspan cable is allowed to start just after the segment is lifted up and is carried out parallel with the segment welding activity so as to speed up the work cycle. As shown in Figure 4B, the alternative work cycle starts with: (1) the backspan cable is installed and stressed, then (2) the segment is lifted up and welded, and at same time the next backspan cable is installed and stressed (also indicated as (2) in the Figure) when the segment is being welded at midspan, then, similar to the original approach, (3) one midspan cable is installed to the just-welded segment, then (4) lifting gear advances to the next segment, then steps (2) to (4) are repeated.

The alternative work cycle was also converted to a SDESA model (Figure 6). The SDESA model for the alternative work cycle is almost the same as the one for the original working cycle. The main difference is in the manipulation of disposable resources which trigger the start of cable installation at the backspan. The disposable resource "+Install BackSp Cable (BACKSP_CB)" is generated on completion of "activity 4: Liftup Segment," instead of being generated at the end of "9 Launching lift gear to next segment" in the original cycle model. The alternative work cycle SDESA model runs on the same activity duration and resource transit time as the ones defined in the previous SDESA model.

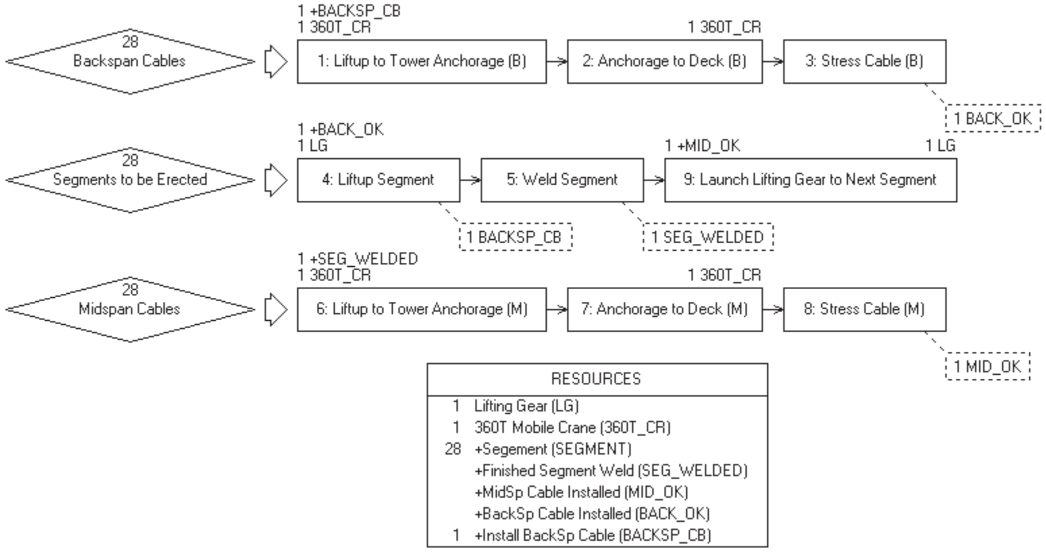


Figure 6: SDESA model of the alternative segment erection approach

5 COMPARISON OF SIMUMATION RESULTS FROM TWO MODELS

Based on the operation simulation results, two observations are made:

- First, the project duration, subject to applying the original work cycle, is 335 days, which is very close to the total segment erection work spent in the real project (about 320 days). The small difference is believed to be due to the learning curve effect (i.e. the operations accelerated in later stages).

However, this close match helps to verify the simulation model.

- The second observation is that the project duration could potentially be shortened by 79 days (i.e. about 25%) if the alternative work cycle is implemented.

Figure 7 shows the activity bar charts generated from the two models. The bar chart shows the installation of the backspan cable is parallel with the welding activity and this synchronous arrangement can shorten the total segment erection time.

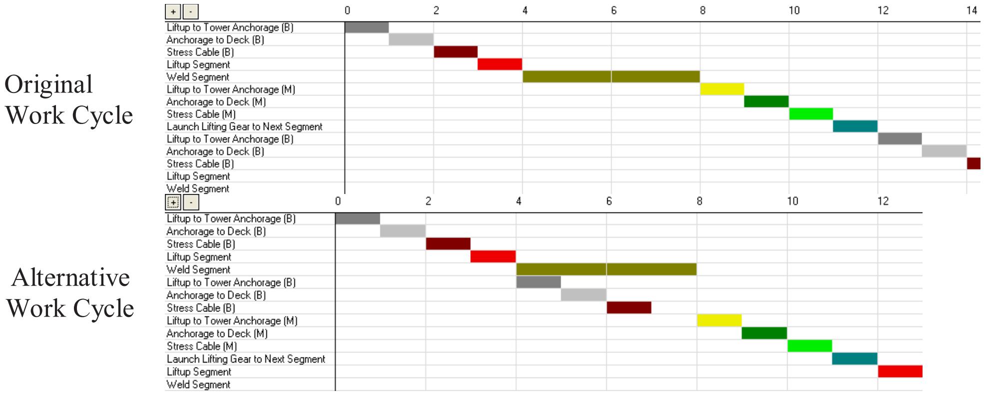


Figure 7: Activity Bar Chart generated from SDESA for the validation and comparison of the two models

6 COMPARISON OF TWO WORK CYCLES FROM THE STRUCTURAL PERSPECTIVE

Based on the operations simulation result, it is obvious that the alternative work cycle is more effective and has the potential to save up 25% of the total segment erection time. However, as structural adequacy is also a critical factor to the constructability of the alternative construction method, the structural perspective of the two different construction approaches are examined and discussed in the coming sections.

A well established structural model helps engineers to justify the adequacy of a structural form in handling certain loading conditions. A loading condition means a combination of loads that impose on a structure at a certain moment. The loading condition during the construction period depends mainly on the positioning of heavy equipment and temporary facilities and the material stacked upon the structure. The equipment, as well as material, is usually represented as resources in operations simulation models, such as SDESA models. By seamlessly linking the resource position and its loading magnitude with an operations simulation model throughout the construction process, the structural performance subject to resource movements and critical activity operations can be estimated for the consideration of the construction engineers.

In this research, we adopted MIDAS for structural analysis in the integrated simulation approach. MIDAS is a total structural solution for bridge design and construction. It provides the functionality of stage construction manipulation, which virtually allows structure models to be built stage by stage. However, as a piece of structural analysis software, MIDAS considers structural performance only in critical construction stages without factoring in elaborate operations planning and project management. In order to link SDESA to MIDAS, we have to (1) first break down the SDESA result into events, then (2) the resources involved in each event are translated to “load group” and “element group” (which form part of the bridge structure in the structure model) in MIDAS, then finally (3) we activate and deactivate the load group and element group, relevant in different stages in MIDAS according to the chronological order of the events extracted from the SDESA simulation model. To link SDESA with MIDAS, the first step is to extract the data at the start event and end event of an activity. The data in each event includes (1) the event time; (2) the activity name, (3) the resource entity required, released or generated, and (4) the event location. This data would be used in MIDAS for the construction stage structural analysis. The use of each type of this data is summarized in Table 1.

Table 1: Mapping between the terminology in SDESA to the meaning in MIDAS

Event Data	**Description of their usage in MIDAS**
Event Time	The chronological order of different construction stages in MIDAS (which means an event in SDESA).
Activity Name	It becomes the name of the construction stage in MIDAS, e.g. "Anchor to Deck (B)" in SDESA will become construction stage name "ET_Anchor to Deck (B) [Start]" and "ET_Anchor to Deck (B) [End]" where the ET is the event time (Figure 8).
Resource Entity	If the Resource Entity is a Reusable Resource, the resource is assumed to be a piece of machinery and the load group in MIDAS will be so named at the corresponding construction stage. The load group is a combination of Resource and Location. That means if the Mobile Crane at the event location segment 5 in that event is being translated, then MIDAS will call the load group "Mobile Crane @ Segment 5." If the Resource Entity is a Disposable Resource generated at the end of an activity, then the corresponding element group combined with the location information will be activated in MIDAS. For example, if the "Backspan Cable Installed" is generated at the event location segment 7 in that event, the element group "Backspan Cable @ Segment 7" will be activated in MIDAS.
Event Location	The start location and end location of the corresponding activity in SDESA. The data will combine with the resource entity information to facilitate the selection of load group or element group in MIDAS.

To illustrate the methodology, the first activity "Lift Cable Head to Tower Anchorage (B)" in the SDESA model (the one for alternative work cycle) is used as an example (Figure 9). When this activity is activated and its end event is reached, a construction stage is formed in MIDAS named "1.00 Lift Cable Head to Tower Anchorage (B) [End]" where 1.00 is the end time of the activity. The resources involved in this event are recorded, including: (1) Tower Crane, (2) Tower Anchorage Team, and (3) 360 ton Mobile Crane (which will be held for the next activity, therefore not shown in the top right corner of the activity). The activity end location is defined as L2, which stands for Location 2: the first tower anchorage point, and differs from the start location L1, which means the first cable unrolling point. As the resources involved in the event are treated as a load group in MIDAS, the load group "360tCr_L2," "TwAnk_L2," and "TwCrane_L2" stand for the 360 ton Mobile Crane at Location 2, Tower Anchorage Team at Location 2, and Tower Crane at Location 2, which are activated in that construction stage in MIDAS while at the same time the corresponding load groups at Location 1 are all deactivated in that construction stage (Figure 10).

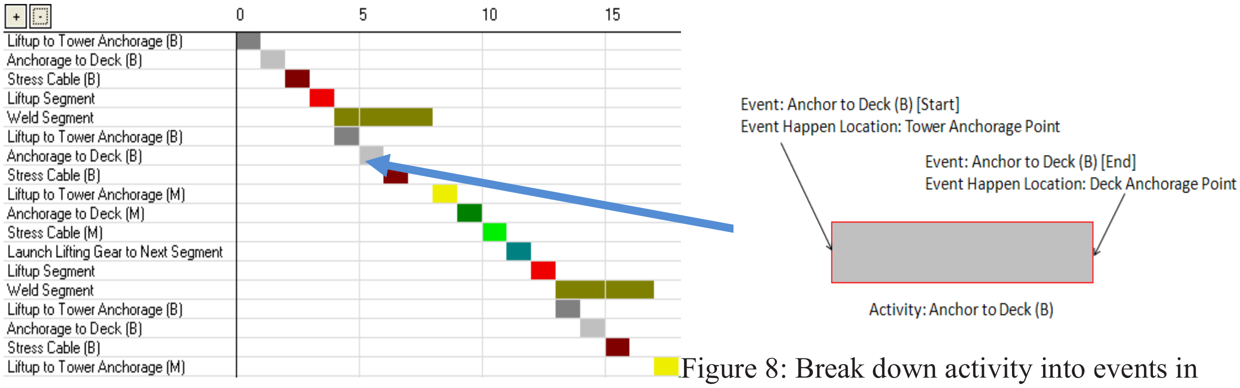
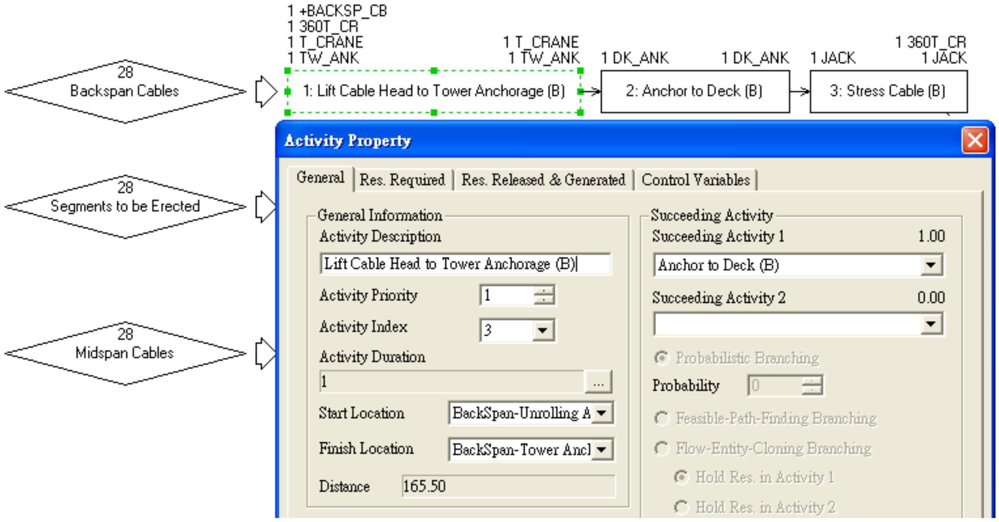


Figure 8: Break down activity into events in SDESA



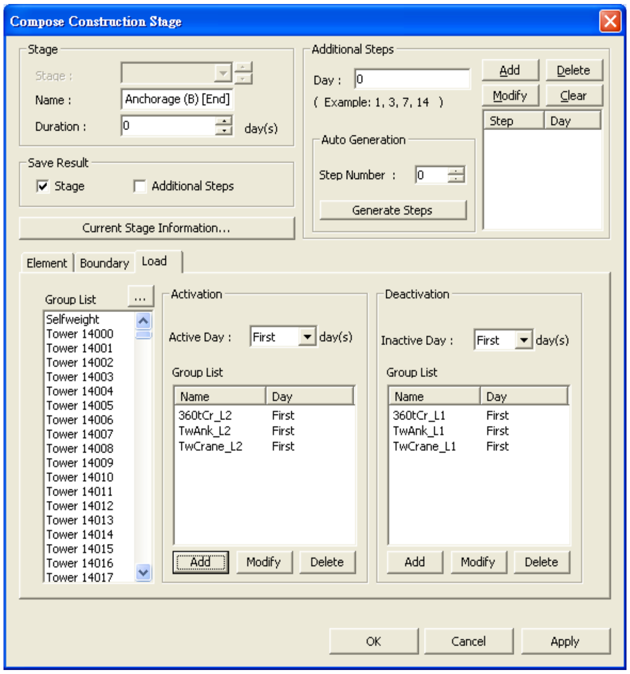
General Information
Activity Description: Lift Cable Head to Tower Anchorage (B)
Activity Priority: 1
Activity Index: 3
Activity Duration: 1
Start Location: BackSpan-Unrolling A
Finish Location: BackSpan-Tower Ancl
Distance: 165.50

Succeeding Activity
Succeeding Activity 1: 1.00
Anchor to Deck (B)
Succeeding Activity 2: 0.00
● Probabilistic Branching
Probability: 0
○ Feasible-Path-Finding Branching
○ Flow-Entity-Cloning Branching
● Hold Res. in Activity 1
○ Hold Res. in Activity 2

Figure 9: Activity Information of "Lift Cable Head to Tower Anchorage (B)"

For the activation of element in the structural model, we may use the third activity "Stress Cable (B)" as the example (Figure 11). When this activity is activated and reaches its end event, a construction stage is formed in MIDAS named "3.00 Lift Stress Cable (B) [End]" where 3.00 is the end time of the activity. In this event the resources involved are recorded and they will be converted into the load group in the same manner in MIDAS as the previous example. However, the disposable resource "BACK_OK" (standing for backspan cable installed) is generated in this event, with the end location of the activity known, the element group is determined to be activated in MIDAS. The element group "BackSpCable@S3" is activated in "3.00 Lift Stress Cable (B) [End]" construction stage, where "BackSpCable@S3" stands for backspan cable for Segment 3 (the first segment in the whole typical cycle) (Figure 12).

Following the above mentioned converting mechanism, the SDESA model results finally transformed into a MIDAS model which portrays the same work procedure in bridge construction.



Name : Anchorage (B) [End]
Duration : 0 day(s)

Save Result
☑ Stage ☐ Additional Steps

Day : 0
(Example: 1, 3, 7, 14)

Step Number : 0

Group List
Selfweight
Tower 14000
Tower 14001
Tower 14002
Tower 14003
Tower 14004
Tower 14005
Tower 14006
Tower 14007
Tower 14008
Tower 14009
Tower 14010
Tower 14011
Tower 14012
Tower 14013
Tower 14014
Tower 14015
Tower 14016
Tower 14017

Activation
Active Day : First day(s)

Group List

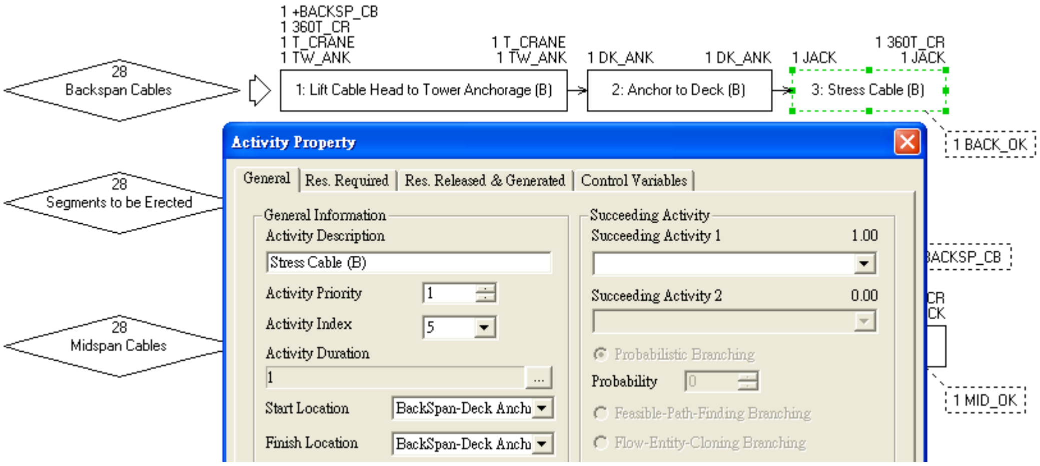
Name	Day
360tCr_L2	First
TwAnk_L2	First
TwCrane_L2	First

Deactivation
Inactive Day : First day(s)

Group List

Name	Day
360tCr_L1	First
TwAnk_L1	First
TwCrane_L1	First

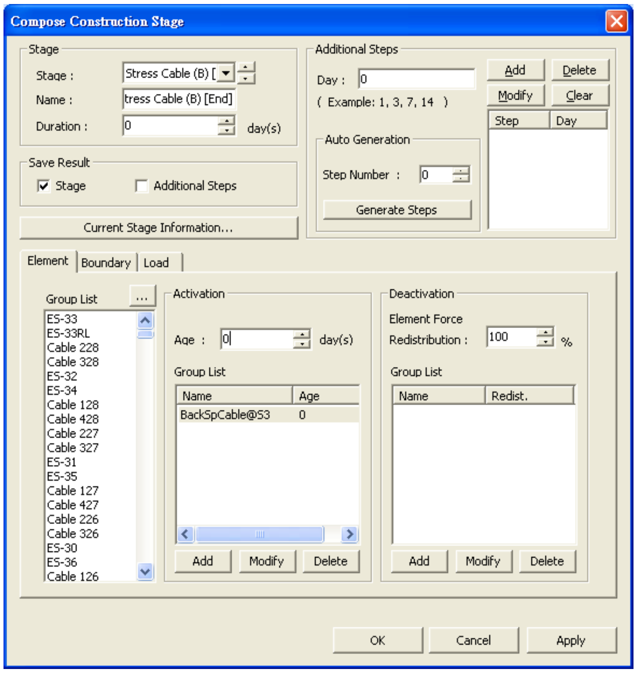
Figure 10: Converting the end event of "Lift Cable Head to Tower Anchorage (B)" into a MIDAS construction stage



General Information
Activity Description: Stress Cable (B)
Activity Priority: 1
Activity Index: 5
Activity Duration: 1
Start Location: BackSpan-Deck Anch
Finish Location: BackSpan-Deck Anch

Succeeding Activity
Succeeding Activity 1 1.00
Succeeding Activity 2 0.00
● Probabilistic Branching
Probability 0
○ Feasible-Path-Finding Branching
○ Flow-Entity-Cloning Branching

Figure 11: Activity information of "Stress Cable (B)"



Stage

Stage : Stress Cable (B) [

Name : tress Cable (B) [End]

Duration : 0 day(s)

☑ Stage ☐ Additional Steps

Day : 0

(Example: 1, 3, 7, 14)

Step Number : 0

Group List:
ES-33
ES-33RL
Cable 228
Cable 328
ES-32
ES-34
Cable 128
Cable 428
Cable 227
Cable 327
ES-31
ES-35
Cable 127
Cable 427
Cable 226
Cable 326
ES-30
ES-36
Cable 126

Activation — Age : 0 day(s)

Name	Age
BackSpCable@S3	0

Deactivation — Element Force Redistribution : 100 %

Name	Redist.

Figure 12: Converting the end event of “Stress Cable (B)” into a MIDAS construction stage

7 APPLICATION OF THE STRUCTURAL ANALYSIS

MIDAS provides all-around functions for structural data analysis. The bending moment, shear force, reaction force at every joint, every member can be obtained in a data list format or a graphical format. Among the various structural response data collected in MIDAS, bending moment, normal force and shear force are of paramount importance to this case study. This is because we will rely on these three parameters to determine whether the alternative segment erection method will potentially lead to the structural failure of the bridge.

The basic mechanism in most structural analysis programs, like MIDAS, is to calculate the distribution of force on the structural member subject to different loading configurations imposed on the whole structure (which is integrated by a number of structural members). The distribution of force depends on the arrangement of structural members, including the geometry, connection characteristics, material and sectional properties of members. Based on the calculation of the structural response, including the bending moment, the normal force and the shear force occur in different structural members, one can get the deformation data as well as the stress development data to determine whether the structure will suffer failure or not.

In this case study, the structural responses of the bridge structure under the two different construction methods are analyzed by MIDAS. To give the reader a feeling of the result presentation, the following figure (Figure 13) shows a screen capture of the structural analysis output in a color-scaled profile format showing the bending moment developed at the bridge structure in one construction stage.

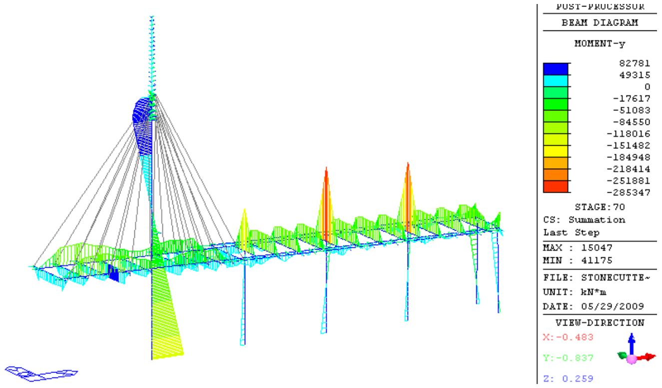


Figure 13: Screen capture of the Bending Moment profile of the MIDAS model

In this case study, the focus is on the stress developed along the bridge tower at each construction stage in the segment erection cycles. The data of (1) Normal Force, (2) Shear Force, and (3) Bending Moment data from MIDAS in the two different segment erection approaches were collected and listed below (Table 2).

Table 2: Changes on the Structural Response due to the Altered Construction Method

	First Typical Cycle (Stage 44 – 48)	**Last Typical Cycle (Stage 254 – 256)**
Deck Displacement (mm)	Diff. = 36; 12% better	Diff. = 475; 18% better
Deck Bending Moment (kNm)	Diff. = 3918; 5% worse	Diff. = 13320; 13% worse
Tower Displacement (mm)	Diff. = 1; Almost the same	Diff. = 1; Almost same
Tower Bending Moment (kNm)	Diff. = 924; Almost the same	Diff. = 178729; 52% better
Cable Force (kN)	Diff. = 172; 3% worse	Diff. = 367; 3% worse

Table 2 summarized the observations on the structural response of the first and last typical segment erection cycle, indicating the benefit or side-effect that the alternative construction method brings to the bridge structure, when comparing to the structural response at the same stage under the original construction method. The first observation of the structure response is that the alternative segment erection method can relieve deck displacement (magnitude dropped by 12-18%) and tower bending moment (magnitude dropped by up to 52%,) whereas the responses in deck bending moment (magnitude increased from 5-13%) and mid-span cable forces (magnitude went up by 3%) became less favorable. Another interesting observation is that the effects on structural responses from the alternative working method become more significant when the midspan cantilever length and tower height increase. Also, the differences of the structural responses **ONLY** happen to the two different steps (i.e. Erect Segment, and Stress Backspan), and no residual interlocking stress remain after those steps. Based on the observations it is highly possible that the alternative working approach can be adopted at the first few cycles (e.g. 1st to 9th segment erection cycles) to speed up the construction process, while starting from a certain cycle, the original construction approach shall be adopted back: when the side-effects to the deck bending moment become significant, when the midspan cantilever length and tower height increase to a certain level.

8 CONCLUSION

In this research article, an integrated simulation approach which allows examination of construction operations in both operations management perspective and structural integrity perspective was proposed. To explore the necessity and feasibility of this integrated analysis method, the proposed method was applied to the Stonecutters Bridge project as a case study. The integrated analysis method shows that the integrated simulation allows engineers to have more comprehensive consideration in formulating construction plans such that it allows them to speed up the working progress without inducing intolerable structural safety risk. The study also demonstrated that the integration of operations simulation and structure modeling is feasible. As the construction management planning cannot be detached from the concept of constructability, it is foreseen that there is a need for the integration of simulation in different aspects to allow better planning and scheduling; however, how to automate the "translation" of data between operations simulation program and structure analysis program would be a new area worthy of research for the sake of a more practical simulation tool for all industry practitioners.

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