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Investigation on the effect of cross beams in single span bridges under dynamic aspect by using finite element method

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ABSTRACT

In the 1980s and 1990s, most bridges in Vietnam employed simple beam for short-span river crossings that did not need navigation and mainly used the reinforced concrete T-beams or pre-stressed concrete. While the T-frame structure that has hang single span is widely applied for rivers that require navigation...The single girder is a basic span made of pre-stressed reinforced concrete T or I cross section, with spacing ranging from 2.2m to 2.6m, and the absence of diaphragms was a common feature of bridges built during this time period. All horizontal crashes almost have happened on the spans that did not have diaphragms. As a result, the impact force is concentrated mostly on the lateral girders, leading to total damage. Thus, researches to evaluate the effect of diaphragms in the distribution of horizontal impact forces as well as minimizing the damage in the span structures are crucial. This study focuses on simulating and studying the influence of the number and position of the diaphragms in terms of stress, deformation and damage when a collision occurs in order to propose additional and repair solutions to enhance the horizontal resistance of span.

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1 Introduction

Many bridges that used T-frame with hang single span were built and all of single spans did not have diaphragms. This type of bridge includes Thai Binh bridge in Thai Binh city which was erected in 1987. Binh bridge, located at Km73+900 on National Highway 37 in Hai Duong Province was erected in 1991. Nong Tien Bridge, located at Km 211+925 on National Highway 37 in Tuyen Quang province was constructed in 1995. An Thai Bridge, erected in 1999, is located on provincial road 388 in Hai Duong Province. In recent years, many bridges of this type have been damaged by ships horizontally, and some girders must be replaced, affecting the normal operating. In the evening of March 6th 2016, The Thanh Luan ship, carrying more than 3000tons, collided with the An Thai Bridge, damaging a pre-stressed reinforced concrete beam with a

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length of 24m. On January 15th 2022, a ship with the registration number HD3839 collided with the Thai Binh Bridge, causing damage to a side girder, forcing the bridge to close and costing more than 2.3 billion VND to repair

In the current simple bridge design process, diaphragms connect main girders and distribute load to the main girders. The load distribution coefficient is used to take into account diaphragm role conversion in bridge design standards such as AASHTO [1] and Euro-code [2]. However, in actual wide-gauge bridge construction, the diaphragm also contribute significantly to the transverse stiffness of the bridge and stabilizes the dynamic structure in the horizontal. Bridge structures that span navigable waterways are inherently vulnerable to barge collisions and must thus be designed for impact loading and sufficient stiffness in the direction of impact. The horizontal stiffness of the bridge ensures the safety of the bridge structure in the case of barge collision incidents and limits the damage on the lateral girders.

Many research and experimental works have been conducted since 1950 to evaluate the problem of ship collision with structure of bridges, and analytical formulas have been provided to validate the experimental model [3]. Previous researchers depicted the girder structure as a rigid system, ignoring the relative rigidity of the vessel and the girder system. Several recent studies[4, 5] demonstrate a correlation between the lateral stiffness of a bridge and the impact of boat collisions. Particularly, the issue of boat collision is further researched and the damage and deformation of the girders are accurately assessed thanks to the powerful development of finite element analysis tools [6, 7].

In fact, a number of lateral collisions have caused severe structural damage, necessitating the replacement of the main girder and resulting in traffic disruption and repair costs. Typically, a collision between the ship and the span of the Thai Binh bridge, which has a deck width of 15.1m and a single span length of 30.4m. The span structure consists of six T- broad flange beam without diaphragm arrangement. The structure of the lateral girder was severely damaged and had to be replaced following the collision. Therefore, it is obvious that stiffening the span structure to resist the impact load needs to be investigated.

The structure of the Thai Binh bridge is analysed based on two issues: the dynamic response of the structure and the dynamic collision problem. The problems are evaluated by modifying numbers and layout of diaphragms. The dynamic stiffness is investigated in order to alter the frequency of the bridge structure's natural vibrations when using diaphragms. The collision problem enables the evaluation of the effectiveness of the reasonable arrangement of the position of the diaphragms on the span structure under the changing ship speed upon collisions, proposing enhanced repair solutions.

2 Modeling parameters

The input data are taken according to “The economic and technical report of Thai Binh bridge” [8]. Material information is summarized in Table 1, and all dimensions of the girder geometry are illustrated in Fig. 1.

Table 1 - Concrete properties

Specification	Note	Concrete	Unit
Compressive strength	f'_c	40	MPa
Elastic modulus	E	29000	MPa
Density	Γ	2400	Kg/m ³
Poisson ratio	μ	0.20	
Tensile strength	$f_t = 0.63\sqrt{f'_c}$	3.98	MPa
Shear transfer coefficient for open crack		0.30	
Shear transfer coefficient for close crack		1.00	

The bridge has a span length of 30.4 meters and a total width of 15.1 meters, with six T-section beams but no diaphragms. One end of the beam is modeled as a fixed pillow, while the other end is modeled as a mobile pillow. The weight of the collision ship is calculated at 10 tons according to the actual ship causing the collision; the collision position is simulated as a block of steel.

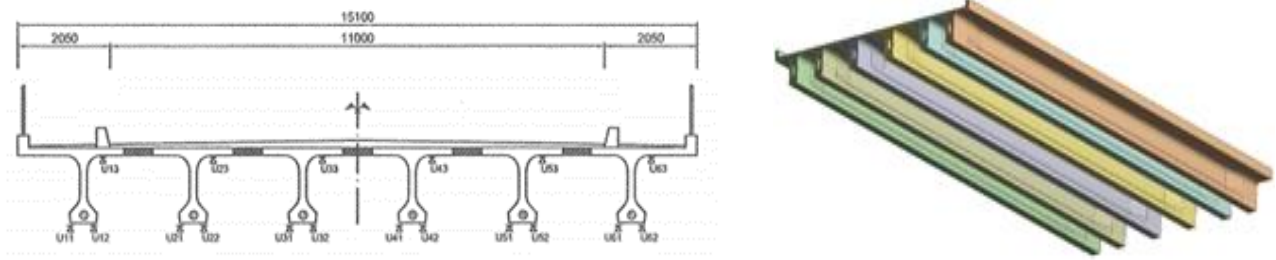


Fig. 1 - Cross section of Thai Binh bridge

The lateral girder, where the collision takes place, has a mesh size of 10mm, which is very fine. Using Tetra underside to solve problems that included explicit analysis and fracture modeling [9, 10]. In special problems, tetra meshes frequently produce more reliable results. The total number of collision problem analysis elements equals 2,259,381 elements. With a large number of elements and an exceptional collision problem requiring a huge amount of computation time and a high performance computer (HPC) configuration, as depicted in Fig. 2.

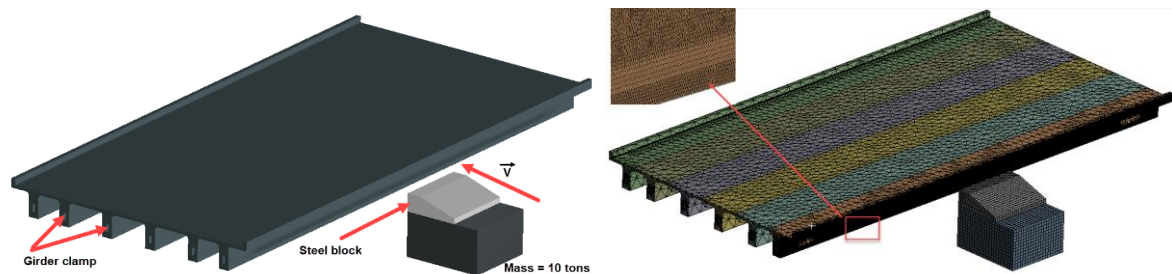


Fig. 2 - Collisions model and meshing

3 Results and discussion

3.1 Structural dynamic response analysis

The natural vibration mode of the bridge is analyzed to determine its structural stability. Natural vibration frequencies are important quantities in structural dynamics, especially in works with complex structures [11, 12]. Simple span bridge structures regularly ignore the structural dynamic stability analysis step. However, the fact that collisions or forced vibration frequencies can affect structural stability in terms of dynamic can result in serious damage.

The dynamic response analysis of the bridge system with 4 cases, as depicted in Fig. 3:

- Case 1: None diaphragm
- Case 2: The span is arranged with 2 diaphragms, the distance to the beam joint is 40cm.
- Case 3: The span is arranged with 3 diaphragms, 2 diaphragms at the top of the girder and 1 diaphragms in the middle of the span.
- Case 4: The span is arranged with 5 diaphragms, 2 diaphragms at the top of the girder, 1 diaphragm beam in the middle of the span and 2 diaphragms equally divided.

The 3D bridge span model is dynamically analyzed using the finite element method in the Modal Analysis module of the software ANSYS 2019 R1.

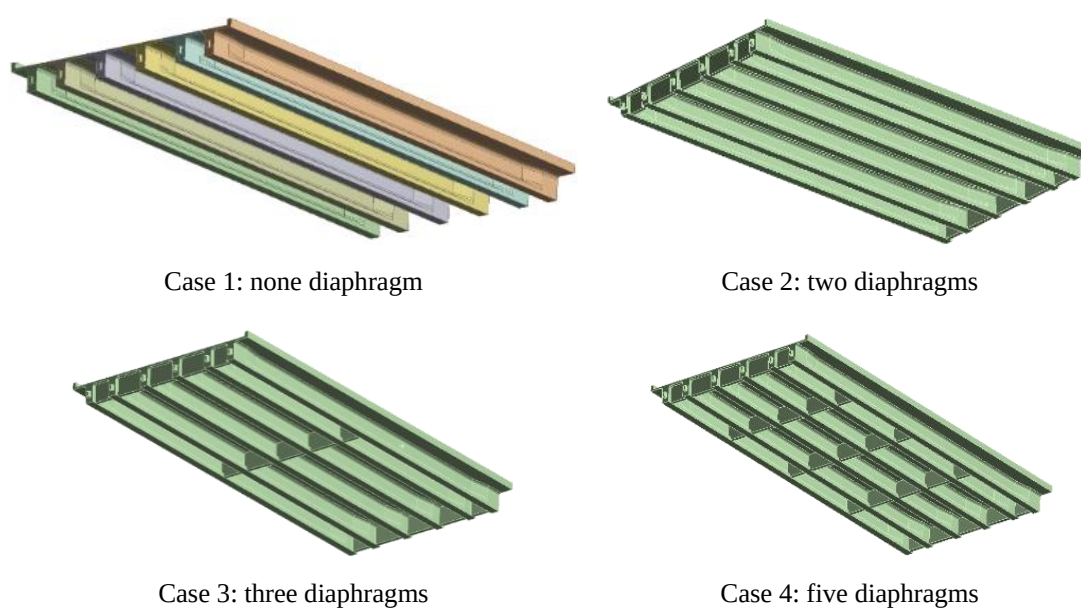


Fig. 3 - Cases of study

Table 2 - The first 10 vibration modes of the span structure

Mode	Frequency (Hz)				Note
	None diaphragm	Two diaphragms	Three diaphragms	Five diaphragms	
1	2.35	2.81	4.33	4.88	
2	3.28	3.49	5.01	5.71	
3	3.64	4.49	10.91	11.63	
4	5.62	6.87	14.22	15.60	
5	6.96	8.28	15.66	16.52	
6	9.13	10.59	16.20	17.21	
7	9.80	10.66	16.66	18.17	
8	12.33	13.98	20.64	21.89	
9	12.72	15.11	22.57	23.22	
10	13.46	16.12	23.61	25.38	

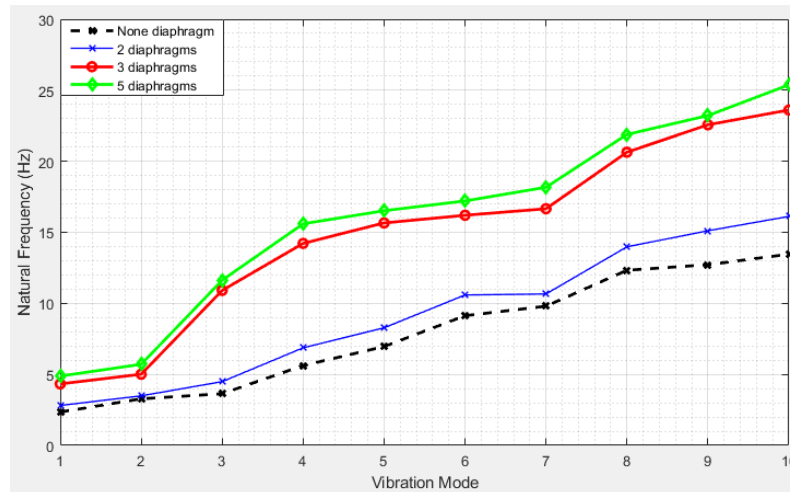


Fig. 4 - Critical frequency corresponding to studied cases

The black line represents the calculation results for case 1 - equivalent to the existing structure without diaphragms - and the blue line represents the calculation results for span with two diaphragms. The red and green lines depict the outcomes of three and five diaphragm layouts, respectively.

The graphic illustrates that the vibration mode in case 1 appears first, followed by the cases without diaphragms. Case 2: Adding two diaphragms does not significantly improve the bridge's lateral stability. Nevertheless, when the number of diaphragms is increased to 3 or 5 beams, the frequency of vibrations increases dramatically. The placement of diaphragms in the middle of the span provides greater stability than the absence of mid-span beams. Case 4 arranges 5 diaphragms but does not significantly improve the dynamic stability of the bridge when compared to the case of 3 diaphragms.

Analyze the mode 3 vibrations in Cases 1 and 3 to clearly see the importance of the diaphragms in the span system. In case 1, the vibration mode of spherical instability occurs at 3.64 Hz and is unstable at two lateral girders of spans. In contrast to the case without diaphragms, this type of vibration occurs at 11.83 Hz much later in case 3 and has a stable displacement in the middle of the span.

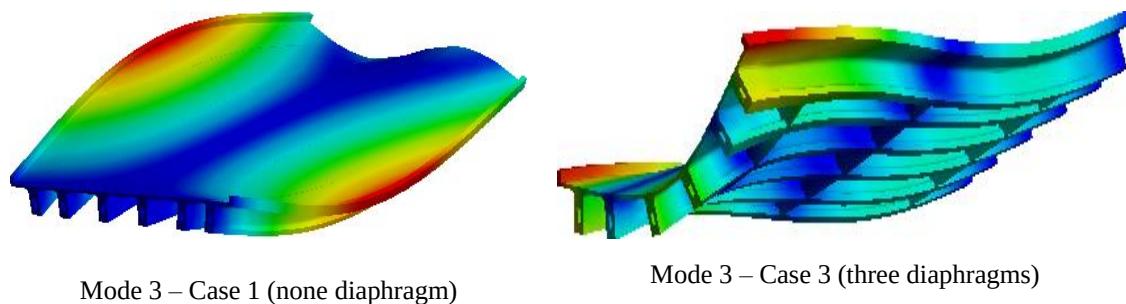


Fig. 5 - Considering the 3rd vibration mode at case 1 and case 3

According to the results obtained, the 3-diaphragms (case 3) provide the most optimal solutions in terms of dynamic stability while also limiting the number of diaphragms arranged on the bridge span.

3.2 Ship collision analysis

The collision problem investigates the effect of the ship collision force on the span structure. In fact, accurately assessing the collision phenomenon when estimating ship speed, ship mass, collision stiffness, or other external factors is difficult. The simulation problem, on the other hand, enables in evaluating the phenomena that may occur during a collision[13, 14]. Based on the Lagrange collision principle [15], the collision problem is simulated using the explicit module of the ANSYS 2019 R1 software.

3.2.1 Collision problem with actual span structure (case 1 – existing bridge)

The span structure is the Thai Binh bridge which is currently in use. A collision incident occurred on January 15th 2022. The lateral girder damaged and necessitating the replacement is illustrated in Fig. 6.

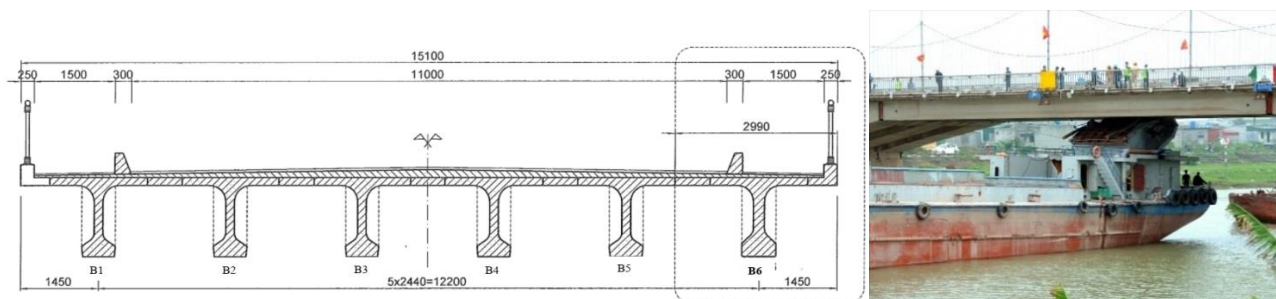


Fig. 6 - Cross section, replace beam No6 and real collided image

Perform a survey simulation with a 10-tons ship, changing the speed by a step of 1km/h for each case to determine the speed that causes structural damage. The results of the stress survey are displayed in Table 4.

Table 3 - The results of the original bridge structure collision analysis

Ship speed km/h	Tensile stress in girder web MPa	Compressive stress in girder web MPa	Compressive stress in bottom of girder MPa	Note
5	3.20	3.52	5.890	
6	3.32	3.76	6.243	
7	3.44	3.99	6.618	
8	3.57	4.31	7.015	
9	3.70	4.65	7.436	
10	3.84	5.03	7.882	
11	3.98	5.43	8.355	Crack
12	4.09	5.86	8.856	
13	4.38	6.33	9.388	
14	4.68	6.84	9.951	
15	5.01	7.39	10.548	
16	5.36	7.98	11.181	
17	5.74	8.61	11.852	
18	6.14	9.30	12.563	
19	6.57	10.05	13.317	
20	7.23	10.85	14.116	Similar to real collided case

Stress assessment at three specific locations on the impacted girder, the tensile stress is highest at the impact surface (located in the web of girder), the compressive stress is highest on the inner web side of the girder. According to observations, the beam starts to crack when the impact speed reaches 11km/h since the tensile stress exceeds the concrete's tensile strength. They are illustrated in Fig. 7.

Continuing the survey while gradually increasing the ship speed to 20km/h, the results indicate that the outer surface of the girder, where the force directly from the collision is applied, is subjected to a high tensile stress. At the girder neck, the maximum tensile stress measured is 7.2 MPa (at the junction between the flange and the girder web). The 7.2MPa of tensile stress is greater than concrete beam tensile strength. When the collision occurs, the maximum shear stress that due to the tearing force is 8.6 MPa in the bottom of the beam. This point close to the impact area, as shown in Fig. 8.

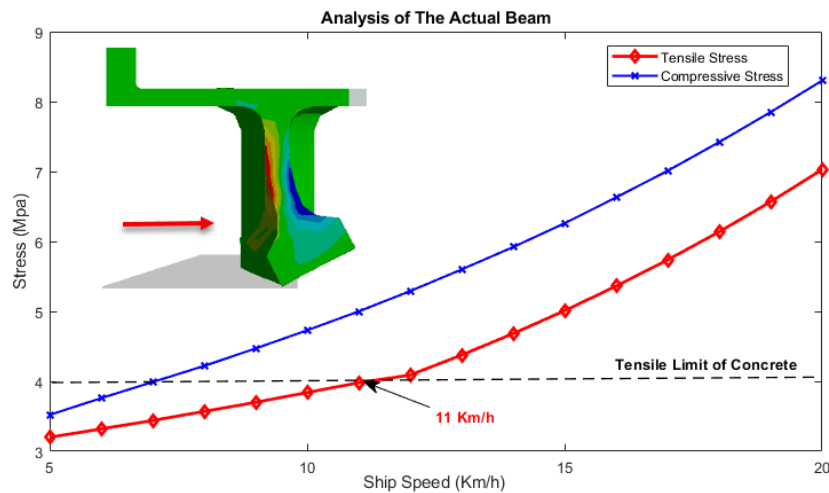


Fig. 7 - Tensile and compressive stresses of girder versus ship speed

Using the Brittle Crack model in the Explicit problem to investigate the creation and growth of cracks, cracks appear and originate from the edges of impact points due to shear stress and large concrete compressive stress when a collision occurs. The cracks immediately start at bottom of girder and then developing with 45° extend gradually to the upper edge of the girder web, where the maximum impact-induced tensile stress exists. The transverse crack area extends along the ship's width where the collision occurred, and the crack depicted in Fig. 9 is similar to the actual crack in the Thai Binh bridge girder after the collision.

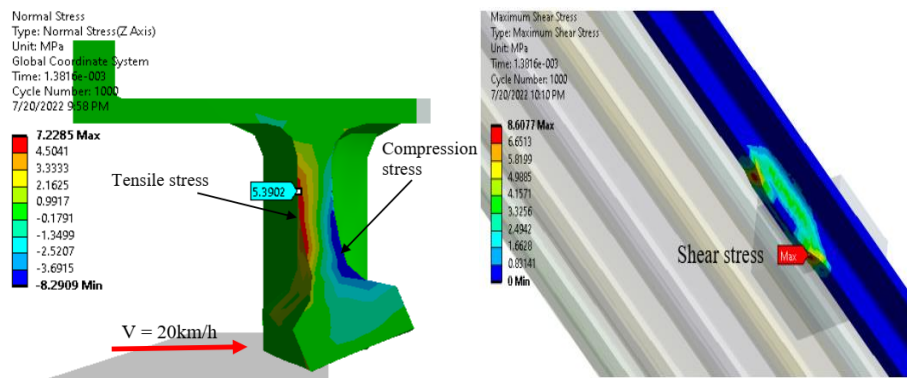


Fig. 8 - Stress field of lateral girder

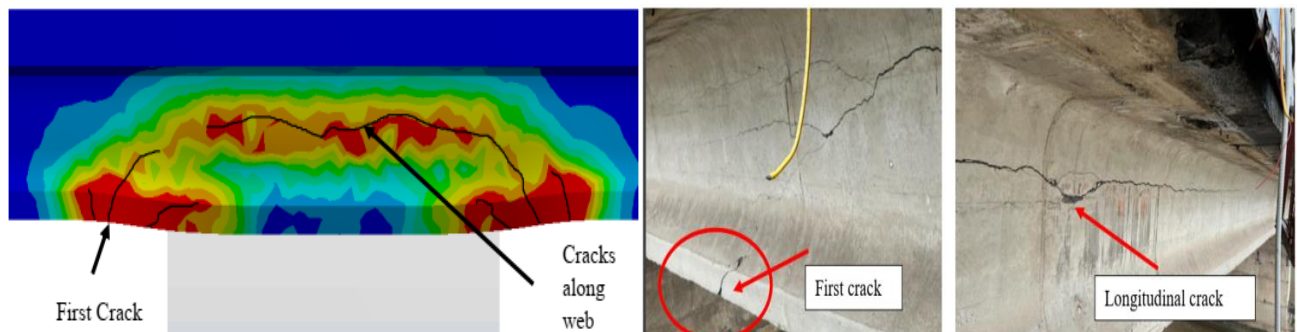


Fig. 9 - Simulated cracks and real cracks

The simulated and actual cracks starting at the bottom of the beam and then ascend the beam's side.

3.2.2 Considering the additional diaphragm cases of 2, 3, and 4

The results of carrying out a comparable simulation analysis with cases 2, 3, and 4 to assess the impact of adding diaphragms are summarized and displayed in Table 4.

Table 4 - Summary of tensile stress in girder web for calculation cases

Ship speed (km/h)	Case 1 (MPa)	Case 2 (MPa)	Case 3 (MPa)	Case 4 (MPa)	Note
5	3.20	2.31	2.08	1.81	
6	3.32	2.44	2.16	1.87	
7	3.44	2.58	2.24	1.94	
8	3.57	2.73	2.32	2.01	
9	3.70	2.88	2.41	2.09	
10	3.84	3.05	2.49	2.17	
11	3.98	3.22	2.59	2.25	Failure at case 1
12	4.09	3.41	2.66	2.31	
13	4.38	3.60	2.74	2.38	
14	4.68	3.80	2.82	2.45	
15	5.01	4.02	2.91	2.52	Failure at case 2
16	5.36	4.33	2.99	2.60	
17	5.74	4.66	3.08	2.68	
18	6.14	5.02	3.17	2.76	
19	6.57	5.41	3.27	2.84	
20	7.03	5.83	3.37	2.92	
21	-	-	3.47	3.01	
22	-	-	3.57	3.10	
23	-	-	3.68	3.19	
24	-	-	3.79	3.29	
25	-	-	3.90	3.39	
26	-	-	4.02	3.49	Failure at case 3
27	-	-	4.14	3.60	
28	-	-	4.27	3.70	Failure at case 4 due to concrete compression
29	-	-	4.39	3.81	
30	-	-	4.53	3.93	

The tensile stress in beams of four cases are shown that: cases 1 and 2 are investigated at 20km/h due to early failures at 11km/h and 15km/h. With 26km/h and 28km/h, the destructive speed for cases 3 and 4 increased significantly. In cases 3, 4, when the number of diaphragms is increased, particularly the role of the mid-span diaphragm, the tensile stress at the girder ribs significantly improves.

Cases 1, 2, and 3 all fail since the tensile stress of concrete exceeds the concrete crack limit. Case 4, with the participation of 5 diaphragms, the tensile stress of the beams is low, but at 30km/h the tensile stress asymptote the concrete limit Fig. 12.

The stress field of the girder span at the time of impact is represented in Fig. 11a. In case 1, the system lacks a diaphragm, and the maximum stress and point of failure are located on the girder neck below the flange. When two diaphragms are added

at the beginning of the girder span (case 2), the position of the maximum stress and the fracture failure line change, and the crack appears on the girder web next to the girder bulb, Fig. 11b.

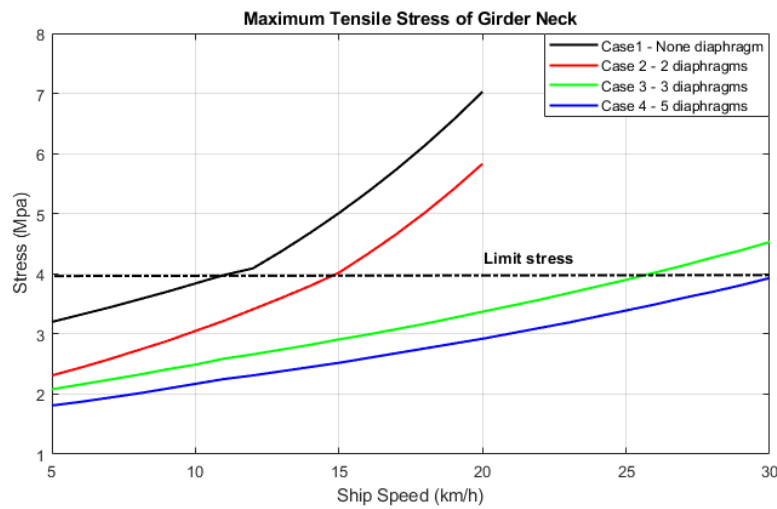
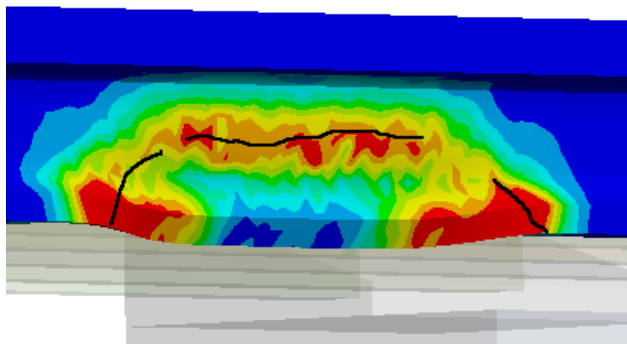
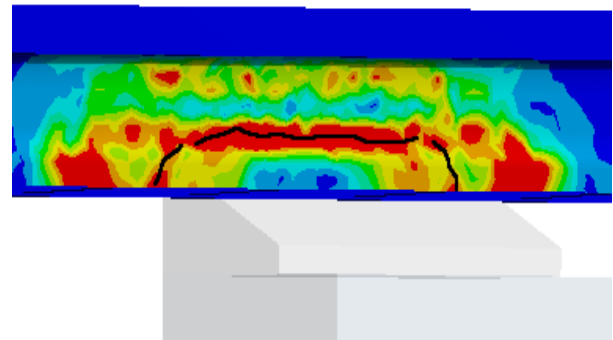


Fig. 10 - Tensile stress in girder web



a) Crack growth in girder of case 1



b) Crack growth in girder of case 2

Fig. 11 - Crack growth analysis of case 1 and case 2

With the addition of two transverse beams, the horizontal rigidity of the girder system is improved, and the ship's speed at which it causes damage increases from 11 to 15km/h. When the tensile stress at the girder changes position from close to the flange to close to the girder, but does not significantly decrease in magnitude, the stiffness of the beam system has increased, but the improvement is insignificant.

As illustrated in Fig. 12, in cases 3 and 4, the compressive stress at the bottom of the beam upon impact is significantly greater than in cases 1 and 2. Due to the distinctive mechanism of the mid-span diaphragm, the increased lateral rigidity of the bridge reduces the tensile stress on the girder, thereby limiting the girder's transverse displacement. Nevertheless, because the diaphragm at the mid-span serves as a bearing and absorber of transverse displacement, it is subject to a high compressive stress.

Only when ship speed reaches 26km/h in case 3 and 28km/h in case 4, the compressive stress at the bottom of the beam exceeds the compressive limit of concrete, resulting in the failure of the beam system due to compression of the bottom concrete.

In contrast to the compressive stress of the girder, when the concrete tensile stress limit is exceeded, the tensile stress will continue to increase due to the propagation of the crack in the longitudinal direction of the bridge at the girder side Fig. 10. However, for cases 3 and 4, when the speed exceeds the limit ($> 28\text{km/h}$), the concrete compressive stress does not

increase and tends to be sideways and drop, because concrete compression does not have a tendency to spread transmission the crack and defects.

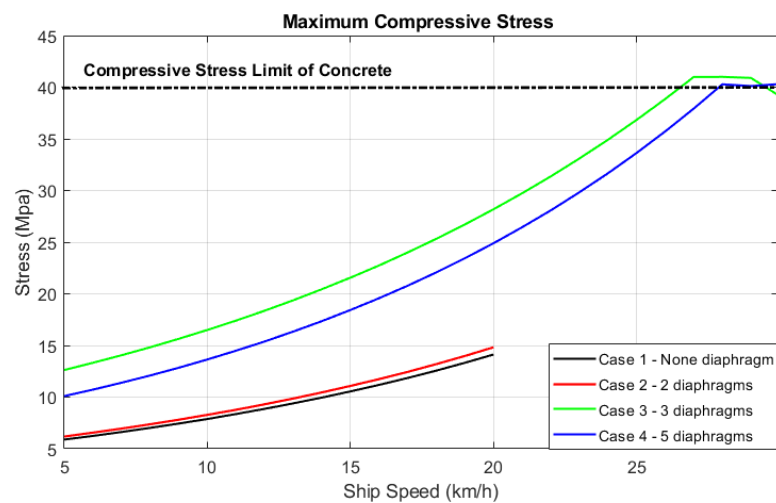
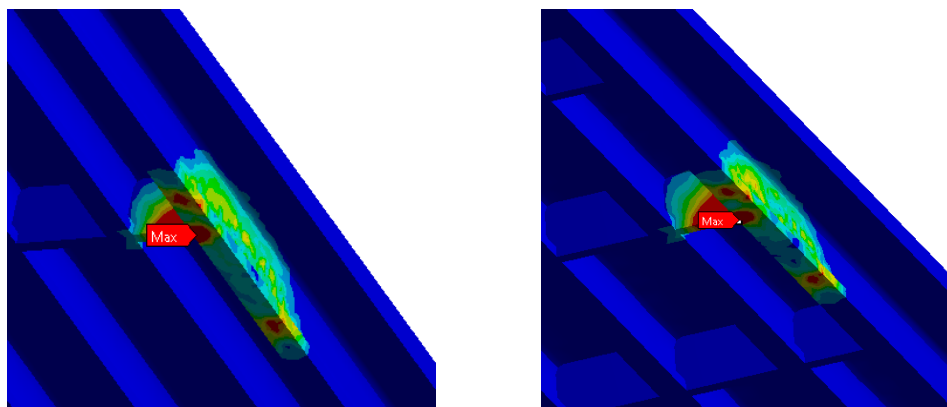


Fig. 12 - Compressive stress in bottom of girder



a- Maximum compressive stress – case 3

b- Maximum compressive stress – case 4

Fig. 13 - Compression failure at case 3 and case 4

In the case of girder spans with three or five diaphragms, there is a diaphragm that coincides with the assumed collision position. When a collision occurs, only the girder bulb and girder bottom are subjected to stress. The diaphragm is responsible for absorbing impact force and transforming it into compressive stress. Cracks at the girder neck can thus be minimized in the case of a large arrangement of three diaphragms. The impact force can only cause localized concrete fracture at the collision area.

Table 4 - Summary of ship speed and causes of failure in collisions

Case studies	Limit speed (km/h)	Cause of failure	Note
Case 1	11	Cracking in girder web	-8.29 MPa
Case 2	15	Cracking in girder web	-6.22 MPa
Case 3	26	Cracking in girder web	Proposed solution
Case 4	28	Compressive broken at the bottom of the girder	

Case 3 has a speed limit of 26km/h for three diaphragms, while case 4 has a speed limit of 28km/h for five diaphragms. The increase from three to five diaphragms does not significantly improve the lateral load capacity. Therefore, to arrange three diaphragms for optimal bearing capacity and cost effectiveness.

4 Conclusions

On the basis of two significant FEM problems, namely the dynamic analysis and the collision problem combined with brittle failure analysis, the complete three-dimensional model of the simple bridge span is analyzed and presented.

The dynamic response analysis and vibration modes of the bridge indicate that the wide-gauge bridge structure with six spans of T-beams and no diaphragm has low lateral dynamic stability and is at risk of failure due to low-frequency resonant forces. The addition of diaphragms significantly improves the structural rigidity by raising the natural frequency of structural vibrations to a higher value.

The collision problem is analyzed assuming that the ship's speed and mass generate effects and crack locations that correspond to reality damage. The cracks appear at the edges of the impact points at the bottom of girders, grow 45° up to the beam neck and traverse around the impact area. In the case of a beam system without a diaphragm, damage occurs at the low impact speed of 11km/h. When the ship speed is 20km/h, the cracks and failure stress fields on the simulation are similar to the actual damage of Thai Binh Bridge. Simulation method provides reliable results of crack types, meet well agreement with the actual phenomena.

The function of the diaphragms in a bridge system utilizing T-beams with broad flanges is proven. When a collision occurs, the addition of diaphragms enhances the structural stability. The number of diaphragms increases the stress minimize gradually in the web of beams. Especially once the diaphragm is positioned in the middle of the girder; it absorbs the impact force and converts it into compressive stress in the concrete. As a result, the stress in the girder neck is reduced, and the girder sustains no damage.

The increase from 3 to 5 diaphragms does not improve lateral load capacity significantly. It is recommended that the arrangement of 3 diaphragms is optimal in terms of force resistance capacity and economy.

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