Behavior Of Composite Steel I-Girder Bridges Under Blast Loads Below Bridge Surface

Ahmed Amer, Walid Attia, Kamel Tamer

Abstract: Bridges play an essential role in the movement of people and goods in and out of cities. Therefore, the bridges are considered susceptible to explosion. The explosion did not only occur as a result of terrorist acts, but can also occur as a result of a collision between two vehicles on the bridge, so it is necessary to understand the effect of these loads on bridges. The main objective of this research is to evaluate behavior of the bridges under blast loads considering different parameters. Also, to study the effect of bridge length on behavior of the bridges subject to blast loads. Hence the analysis would refer to the most popular bridges. A girder bridge with concrete deck, particularly steel girder bridge, is the most popular constructed in the world. Based on the results, two modes of failure are noticed as a results of loaded bridges by blast loads. Bending failure mode occurs in case of blast at mid-span and shear failure mode occurs in case of blast at span ends. Reinforced concrete slabs is more prone to failure in case of the blast at mid-span than blast at span ends but steel girder is more prone to failure in case of the blast at span ends than blast at mid-span. Steel girder failure is the key cause of the bridge failure but the reinforced concrete slabs do not cause bridge failure. Area collapsed in reinforced concrete slab is inversely proportional to the length of bridge. Also, steel girders became less prone to failure with increasing bridge length.

Index Terms: composite Bridges, Blast loads, Non-linear analysis, Explosive weight, Behavior of bridges.

1. INTRODUCTION

Bridges and roads play an important role in passengers and freight transport in the world. Therefore, the bridges are considered to be vulnerable to explosion through terrorist attacks or as a result of collision of two vehicles. Blast load will lead in cracks occurring in the slab bridge. Unless the cracks are not repaired, deterioration of the steel reinforcement and concrete spalling will eventually occur. It limits the bridge lifetime and higher repair costs. If the explosive size is high, flexural cracks can propagate in all directions and cause yield in steel girders, which may result in a bridge collapse such as the collapse of Interstate 285 Bridge over GA-400 in the Atlanta as shown in Fig. 1.

***Fig. 1**. Interstate 285 Bridge over GA-400 in the Atlanta*

Therefore, it is necessary to understand the effect of blast loads on bridges to avoid collapses. The main objective of this paper is evaluate the effect of different parameters on behavior of the bridges under effect blast loads such as explosive weight, the distance from the explosion source to bridge, and position of explosion. Also, study the effect of bridge length on behavior of the bridges subject to blast loads. Hence the analysis would refer to the most common bridges. A girder bridge with concrete deck, particularly steel girder bridge, is the popular constructed in the world. Steel I-girder bridges are also more vulnerable to failure due to blast loads approximately 77 percent of the other bridges [1]. Finite Element Method (FEM) were used to predict the behavior of bridges under effect of blast loads. In this study, finite element program ABAQUS was used in order to carry out nonlinear analysis on composite steel I-girder bridges. Bridge was loaded by blast loads below the bridge surface. In this study used the biggest three explosive weights (W) are selected depend on the loading capacity of different exploded vehicles are (Pick-up truck, Van, and Truck).

2. BACKGROUND

2.1 Explosions

The concept of an explosion is a fast release of energy into the atmosphere that generates a blast wave. There are many types of explosion that can be split into physical, chemical, and nuclear explosions. A chemical explosion is the most popular explosives that can occur accidentally or caused by the terrorist attacks. The key cause of the chemical explosion is the fuel elements' rapid oxidation, it can be liquids or in condensed solid forms. Table 1 shows the explosive weight of the different explosion were determine according to the loading capacity of a different vehicle [2].

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TABLE 1

THE WEIGHT OF THE DIFFERENT BOMBS

Carrier	Explosive weight (Kg)
Hand Carry Bomb	10
Motorcycle	50
Medium Car	200
Large Car	300
Pick-up truck	1400
Van	3000
Truck	5000

2.2 Characteristics of Blast Wave

The blast characteristics define a transient pressure pulse that rapidly radiates out of the explosion's position. At the moment when the blast wave reaches a structure, the peak pressure (P_{so}) is reached instantaneously and then the pressure decreases rapidly as shown in the blast wave pressure-time profile in Fig. 2. There are two major phases from the pressure-time profile: positive phase and negative phase. Positive phase is the component above atmospheric pressure and is called negative phase under atmospheric pressure. On the other hand, the positive pressure phase is not seen in most burst analyzes since the negative phase is longer duration and less strength than the positive duration so the negative pressure phase effect is marginal compared to the positive pressure phase [3-5].

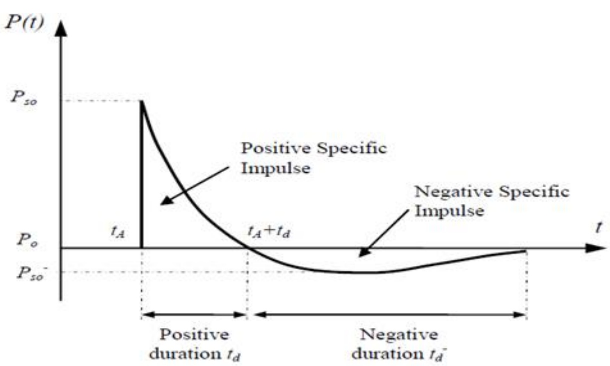


***Fig. 2**. Typical the blast wave pressure-time profile*

2.3 Blast Scaling Low

Blast scaling is the major variable for measurement of the blast load. The scaled distance is used to compare explosions with different weights of charge and distance between blast sources to structure. The pressure and velocity of the blast wave reduced with this distance increasing. Hopkinson [6] first introduced the most common form of blast scaling, and is referenced by Baker [7] and takes the following form in Equation 1.

$$Z = R/W^{1/3} \tag{1}$$

Where Z is the scaled distance in (m/kg$^{1/3}$); R the distance from the detonation source to structure in (m); W the TNT equivalent weight in (Kg).

2.4 Methods for Determination of Blast Pressure

Different relationships and approaches exist to calculate the maximum positive overpressure during the free air blast. All relationships include measurement of the scaled distance, which depends on the distance from the source of detonation to the structure and the corresponding weight of the TNT. Different studies have been performed and the following equations have been derived based on the analysis of large sets of experimental data for calculating blast pressure [8-14].

- Brode, 1955

$$P_{so} = 0.67/Z^3 + 0.1 \quad \text{For } P_{so} > 1 \tag{2}$$

$$P_{so} = 0.0975/Z + 0.1455/Z^2 + 0.585/Z^3 - 0.0019 \quad \text{For } .01 \leq P_{so} \leq 1 \tag{3}$$

- Newmark, 1961

$$P_{so} = 0.6784(W/R^3) + 0.93(W/R^3)^{1/2} \tag{4}$$

- Mills, 1987

$$P_{so} = 1.772/Z^3 - 0.114/Z^2 + 0.108/Z \tag{5}$$

Where P_{so} is the maximum positive pressure (MPa); R the distance from the detonation source to structure in (m); W the equivalent charge weight (kg); Z the scaled distance in (m/kg$^{1/3}$).

- Unified Facilities Criteria, 2008

Introduced a chart to calculate the maximum pressure and blast durations for free-air burst as shown in Fig. 3.

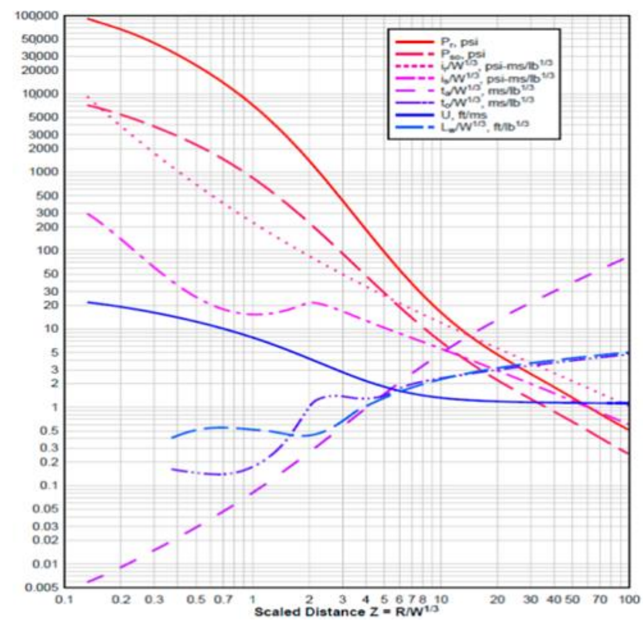


***Fig. 3**. Positive phase shock wave parameters for explosion on free-air*

3. METHODOLOGY

3.1 Study Bridge Description

Composite steel I-girder bridge with a simple span, Fig. 4 shows the component and dimensions of this bridge. The bridge's numerical model was restrained at both ends using hinge and roller supports. The Composite steel I-girder bridge was designed according to new Egyptian Code (ECP 201:2012) for live load, dead load and impact load to obtain cross section of steel girders and reinforcement detailing of concrete slabs as shown in Fig. 5 [15, 16].

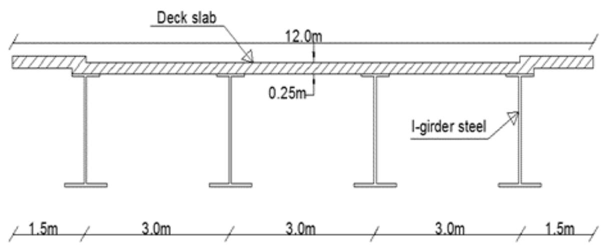


***Fig. 4**. Cross section of composite steel I-girder bridge*

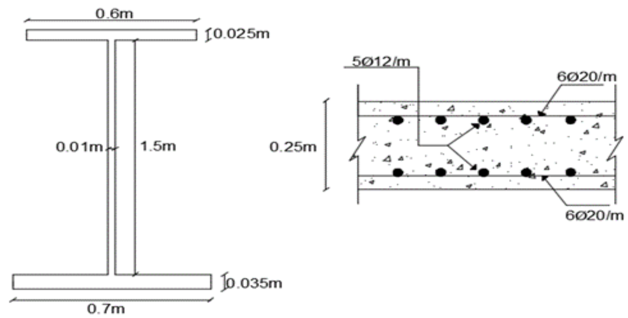


***Fig. 5**. Steel girders dimension and reinforcement of slab*

3.2 Blast Loads

Bridge was loaded by blast loads, it is applied at mid-span below the center axis between the two inner girders, at mid-span directly below the inner girder, at span ends below the center axis between the two inner girders, and at span ends directly below the inner girder. In this study used the biggest three explosive weights (W) are selected depend on the loading capacity of different exploded vehicles are (Pick-up truck, Van, and Truck) and standoff distances (R) used in the study are (1.0m, 1.5m, 2.0m, 2.5m, and 3.0m) to predict the behaviour of the bridge under effect these loads.

3.3 Finite Element Modeling (Non-Linear Analysis)

In this study, the bridge was modeled using software for ABAQUS nonlinear finite element analysis. The solid element is used to model the concrete slab; the beam element is used for modeling the steel girders' flanges and web; and the truss element is used for modeling reinforcement of the deck system. Also in this study, the girders are fully composite with the concrete slab during the nonlinear analysis behavior as shown in Fig. 6. Table 2 shows the materials properties of reinforced concrete and steel [17, 18]. Table 3 shows the list of loading cases for the bridge.

***Fig. 6**. Model of composite steel bridge using ABAQUS*

TABLE 2

MATERIAL PROPERTIES USED FOR THE BRIDGE ANALYSIS

Concrete		Steel section		Reinforced bars
Density 2400 kg/m^3		Density 7800 kg/m^3		Density 7800 kg/m^3
Uniaxial comp. 26.8 MPa		Yield stress 355 MPa		Yield stress 400 MPa
Uniaxial ten. 2.39 MPa		Ult. Stress 530 MPa		Young's mod. 210GPa
Young's mod. 22.9GPa		Young's mod. 210GPa		Poisson's ratio 0.3
Poisson's ratio 0.2		Poisson's ratio 0.3		
Stress (MPa)	Plastic strain	Stress (MPa)	Plastic strain	
6.42	0.0	355	0.0	
9.33	0.0001	425	0.05	
10.69	0.00015	485	0.1	
17.05	0.00042	512	0.15	
19.70	0.00056	527	0.2	
25.1	0.00098	529	0.25	
26.8	0.00139	530	0.3	

TABLE 3

LIST OF MULTI-CASE OF BRIDGE LOADING

Explosive weight (Kg)	Location of blast	Standoff distance (m)	Number analysis of bridge
(1400,3000,5000)	between girders at mid-span	(1,1.5,2,2.5,3)	15
	centered on girder at mid-span	(1,1.5,2,2.5,3)	15
	between girders at span end	(1,1.5,2,2.5,3)	15
	centered on girders at span end	(1,1.5,2,2.5,3)	15
Total number of bridges			60 Bridges

4. RESULTS

The model shows that part of reinforced concrete slab and some steel girders arrived to the stage of failure. This depends mainly on the distance from the detonation source to bridge surface and the relative strength/ductility of the bridge elements. Two modes of failure was noticed as a results of loaded bridge by blast loads. In case of blast at mid-span, the failure mode is bending failure occurs in the mid-span of bridge because of applied bending stress exceeds the bending capacity of bridge elements. This failure is characterized by initial concrete slab cracking, tensile reinforcement yielding, concrete slab compression failure, and steel girders yielding. In case of blast at span end, the failure mode is shear failure occurs near the supports of bridge because of applied shear stress exceeds the shear capacity of bridge elements.

4.1 Results of Nonlinear Analysis of Composite Steel Girder Bridge due to Blast below Bridge Surface

- The bridge model indicates that explosion impact caused the arrival of concrete and reinforcement to the stage of ultimate and create a hole in the deck slab. The area that collapses in reinforced concrete slab is directly proportional to the charge weight (W) and it inversely proportional to the distance from the explosion source to bridge surface (R) in all cases. In the case of blast at mid-span, reinforced concrete slab is more prone to collapse than in the case of blast at span ends in all cases as shown in Fig. 7 and Table 4. This table also shows that reinforced concrete slab is more prone to collapse in case of blast between girders than centered on girder in all cases.

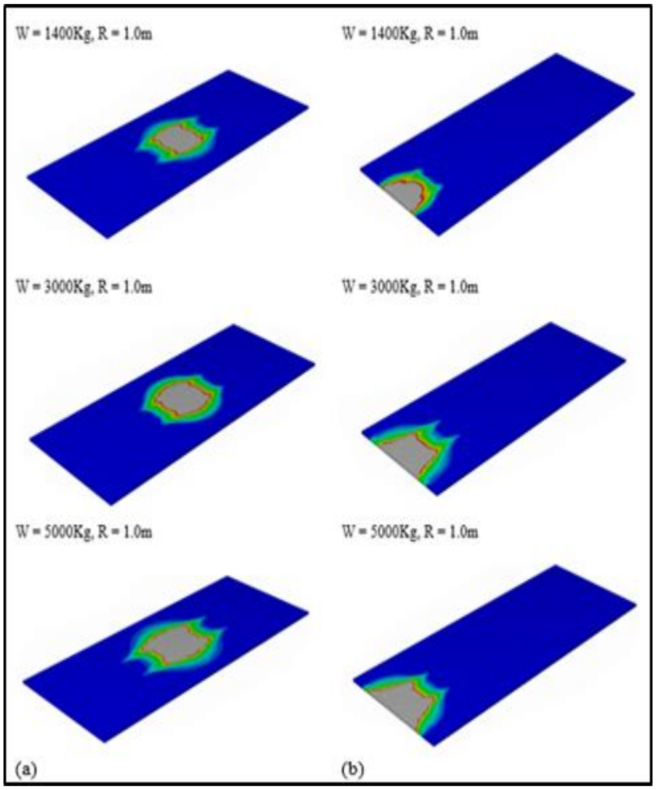


***Fig. 7**. Area collapsed in concrete slab at blast below the bridge (a) mid-span; (b) span end*

TABLE 4

RATIO OF COLLAPSED SLAB AREA TO THE TOTAL SLAB AREA AT BLAST BELOW THE BRIDGE

Blast weight (Kg)	Standoff distance (R)	Area collapsed (mid-span)		Area collapsed (span end)	
		between girders	centered on girder	between girders	centered on girder
1400	3.0m	No	No	No	No
	2.5m	No	No	No	No
	2.0m	No	No	No	No
	1.5m	2.3%	2.25%	2.0%	1.7%
	1.0m	3.9%	3.4%	2.9%	2.6%
3000	3.0m	No	No	No	No
	2.5m	No	No	No	No
	2.0m	1.8%	1.6%	1.5%	1.25%
	1.5m	3.2%	2.9%	2.6%	2.3%
	1.0m	5.0%	4.5%	4.0%	3.6%
5000	3.0m	No	No	No	No
	2.5m	1.75 %	1.5%	1.6%	1.4%
	2.0m	2.7%	2.4%	2.15%	1.8%
	1.5m	4.2%	3.7%	3.5%	3.2%
	1.0m	6.0%	5.4%	5.1%	4.2%

- Steel girder failure is the key cause of the bridge collapse but the reinforced concrete slabs do not cause bridge collapse so the critical case is blast loads applied at span end directly below an interior girder and standoff distance equal to 1.0m. Also, Steel girders are more prone to failure in case of blast at span end than mid-span as shown in Fig. 8 and Table 5.

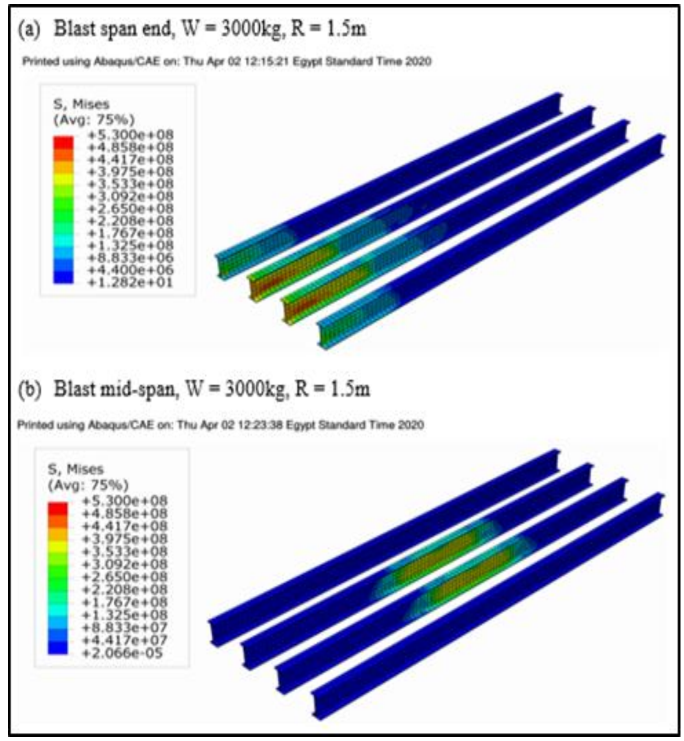


***Fig. 8**. Comparison between maximum stresses of steel girders at blast below the bridge*

TABLE 5

STATE OF STEEL GIRDERS AT BLAST BELOW THE BRIDGE

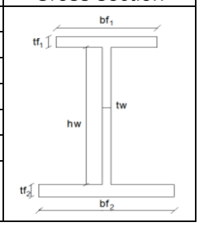
Blast weight (Kg)	Standoff distance (R)	Steel girder collapse (mid span)		Steel girder collapse (span end)	
		between girders	centered on girder	between girders	centered on girder
1400	3.0m	No	No	No	No
	2.5m	No	No	No	No
	2.0m	No	No	No	No
	1.5m	No	No	No	No
	1.0m	No	No	No	Partially
3000	3.0m	No	No	No	No
	2.5m	No	No	No	No
	2.0m	No	No	No	No
	1.5m	No	No	No	Partially
	1.0m	No	Partially	No	Partially
5000	3.0m	No	No	No	No
	2.5m	No	No	No	No
	2.0m	No	No	No	Partially
	1.5m	No	Partially	No	Partially
	1.0m	Partially	Partially	Totally	Totally

4.2 Results of Effect of Bridge length on Behavior of the Bridges Subject to Blast Loads.

This effect must be studied in the critical case. The critical case is blast loads applied at span end directly below an interior girder, standoff distance equal to 1.0m, and explosive weight equal to 5000kg. Six different bridge spans are studied, 24, 30, 36, 42, 48, and 54 meters to predict the behavior of the bridges under blast load. These bridges were designed according to new Egyptian Code (ECP-201:2012) for live load, dead load and impact load to get cross section of steel girders. Table 6 shows the designed steel girder section of different bridge spans [16].

TABLE 6

STEEL GIRDER DIMENSIONS OF DIFFERENT BRIDGE SPANS

Bridge span	Steel girder dimensions (cm)						Cross section
	bf_1	bf_2	tf_1	tf_2	hw	tw	
24	50	70	2.5	3	125	1	
30	60	70	2.5	3.5	150	1	
36	60	75	3	4	160	1	
42	65	80	3	4.5	180	1	
48	70	90	3.5	5	180	1	
54	80	105	3.5	5	190	1	

- The model shows that the blast made a hole in the deck slab as a result of the arrival of concrete and reinforcement to the stage of ultimate. Area collapsed in reinforced concrete slab is inversely proportional to the bridge length as shown in Fig. 9 and Fig. 10.

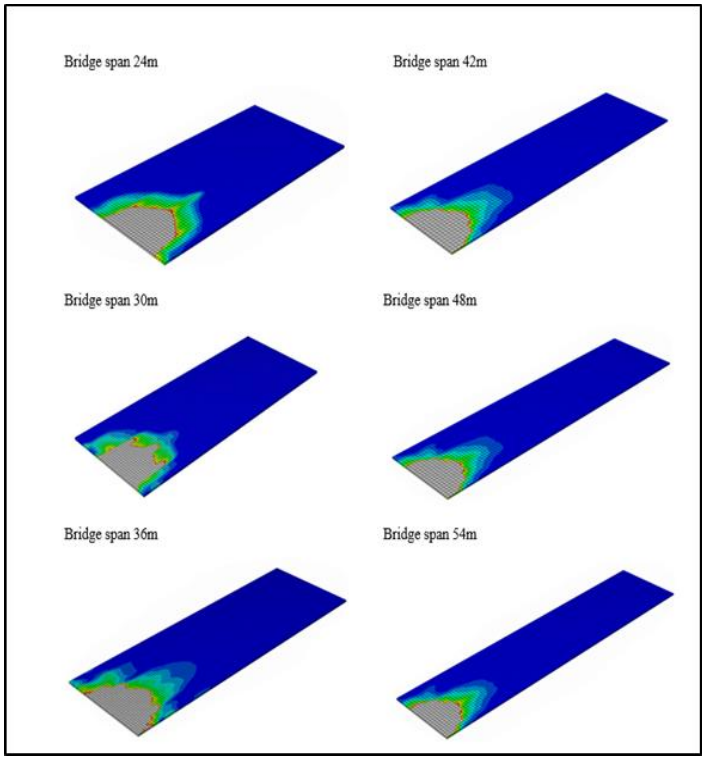


***Fig. 9**. Area collapsed in concrete slab at different bridge span*

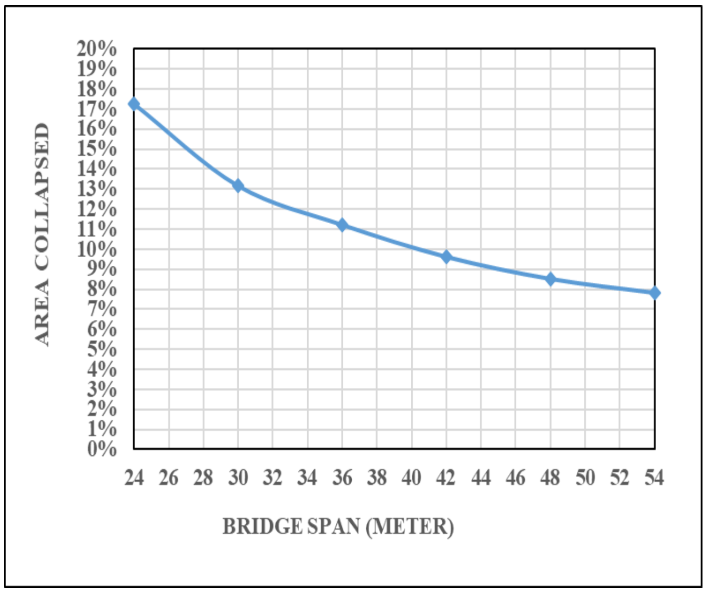


***Fig. 10**. Relationship between different bridge spans with percentage of area collapsed in reinforced concrete slabs*

- Steel girders became less vulnerable to collapse with increasing bridge length as shown in Table 7

TABLE 7

STATE OF STEEL GIRDERS OF DIFFERENT BRIDGE SPANS

Bridge Span (m)	Steel Girders
24	Totally collapsed of the girder directly above the blast and no collapsed of other girders
30	Totally collapsed of the girder directly above the blast and no collapsed of other girders
36	Lower flange and web of the girder directly above the blast collapsed and no collapsed of other girders
42	Lower flange and half web of the girder directly above the blast collapsed and no collapsed of other girders
48	Lower flange and half web of the girder directly above the blast collapsed and no collapsed of other girders
54	Half web of the girder directly above the blast collapsed and no collapsed of other girders

5. CONCLUSIONS

1. Two modes of failure are noticed as a results of loaded bridges by blast loads. Bending failure occurs in case of blast at mid-span and shear failure occurs in case of blast at span ends.
2. Bridges failure are directly proportional to the explosive weight and inversely proportional to the distance from the detonation source to bridge surface.
3. Reinforced concrete slab is more prone to failure in case of blast at mid-span than in case of blast at span ends in all cases and especially case of blast at between girders.
4. Steel girders are more prone to failure in case of blast at span end than in case of blast at mid-span especially in case of centered on girder.
5. Steel girder failure is the key cause of the bridge collapse but the reinforced concrete slabs do not cause bridge collapse.
6. Totally collapse occurred in the girder directly above the blast when is subject to explosive weight 5000kg but without a total collapse of the bridge.
7. Area collapsed in reinforced concrete slab is inversely proportional to the length of bridge. Also, steel girders became less vulnerable to collapse with increasing bridge length.

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