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An Investigation on the Seismic Behavior of Castellated beams under Explosion Loads Effect

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Abstract

Due to the widespread use of ceilings with T-shaped beams as well as because of economic problems and the lack of sufficient variation of rolled profiles, applying castellated beams in buildings with steel structure has become quite common. Therefore, the present study aims to investigate the behavior of castellated beams with rigid and semi-rigid connection and surrounding in and non-surrounding in concrete under blast effect. The same pattern was modeled in Abaqus software and the cyclic load was introduced in the form of a domain to the software. The results showed better performance of the beam in rigid connection compared with semi-rigid connection against explosion. Moreover, binge surrounded in concrete causes the castellated beams to perform much better than non-buried mode and improves various drawbacks of the castellated beams. Castellated beams failure mode in the cyclic load is at the same time failure mode (local lodge of lower wing in front of the first opening after the connection) that this deficiency is largely eliminated by adding a reinforcement plate wing.

Keywords: Castellated beams, Explosion Loads, Seismic Behavior.

Introduction

A building during its useful life faces many threats. These threats are classified into two categories: natural and man-made. Natural threats normally exist in any structure and are considered in all designs as earthquakes, fires, storms, and floods. Man-made threats consist of a variety of air, and land offenses, terrorist operations, bombing, explosion and more.In the past, designing the structure was restricted to loads resulted from an explosion in military and industrial buildings aiming to confront with loads originated from military and industrial explosions. However, during the last years and due to increasing terrorist attacks around the world, other buildings like commercial, political and social buildings or any other important building have been a target of such attacks. Meanwhile, some specific buildings are more at risk compared with other structures. Therefore, most countries have conducted many investigations and provided several manuscripts and instruction about the effects of explosion, its impact on the structure, and designing and analyzing the structure under this load.To mention some, FEMA 426, (2003), FEMA 427, (2003) and TM5-1300, (1990) in the U.S. are important. Since the castellated beams are widely used in the construction industry and they are one of the significant elements of steel structures, and because of economic problems besides the lack of any diverse rolled profiles, the castellated beams have been extensively applied on material structures. The beam buries in concrete while concreting ceiling inevitably. Due to the necessity of understanding and performance of this type of beam under the influence of explosion in buildings and because of the lack of researches on this subject, the present study aims to investigate the seismic behavior of castellated beamssurrounding in and non -surrounding in concrete under the blast effect.

In recent years lots of studies have been concentrated on the performance and the behaviors of steel connections under the blast effect. One of the frequently reviewed references is the Army Technical Manual (TM5-1300). This manual has only provided some general ideas about the necessity of designing steel connections against explosion and has not presented any specific details for such systems. Houghton and Karns, (2003) worked on analysis of finite elements of side plate

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connections against blast load. Sabuwala et al, (2005) studied the behavior of quite rigid connections under blast load. They also investigated the connection system of the web side plate to column and welded plate to the flange system. The studies were done through the finite element method and the tests have shown that plate connection welded to the flange, displays a good performance under blast load and has reduced the existing stress in the connection place.Liew and Chen presented a numerical analysis of rigid frames under explosion and fire. Although the overall response was concentrated on the total frame response, they used end forces of components for determination of the connections elements resistance in order to validate the rigid frame analysis. The Chen and Liew, (2005) study includes a detailed description of the structure behavior dependent on the loading under rapid strain and the impact of increased temperature on the results.Krauthammer and Cipolla, (2007) concluded that the analysis of finite elements of steel frame structures is very sensitive to the various modes of connection failure. They studied on non-linear analysis of flexural rotation of connections in steel structures for rigid and semi-rigid connection types. In the steel structures , castellated beams are important elements , due to the weakness of the castellated beams, several studies have been done on the conventional loadings, but the performance of these beams have not examined under the blast effect so far. Therefore, the present study aims to examine the castellated beams behaviors under the blast effect as well as identifying weak points of these beams under the impact of such loadings.

Research background

Kerdal and Nethercot, (1984) evaluated a few samples and discovered that due to the weaknesses of conventional beams, castellated extensive research have been done on this , but the function of these beams under blast has not been studied various modes of failure of the castellated beams. The results showed 7 types of failure, two of them are associated with similar web and others belong to open web (the castellated beams). Hosseini and Nategholahi, (2003) empirically examined modes of failure of the castellated beams under the seismic forces, according to Manual # ACT-24, (1992). The tests showed that the first web after the first beam opening, the failures begin there and were influenced by two separate and cyclic loads.

MATERIALS and METHODS

Mechanical properties of the models

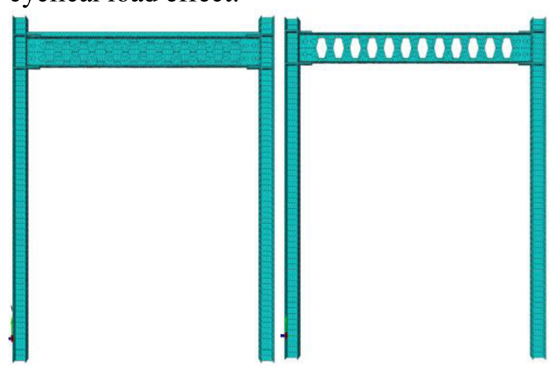
In all samples, for steel beam and columns and plates used for the connection and steel yield stress of 240 MPa, and ultimate level stress of 360 MPa, the behavioral pattern of steel in form of bilinear and the ultimate compressive strength at 28 days, a cylindrical specimen of 24 MPa was considered.

Table 1. Characteristics of used steel

	F_y , N/m^2	F_u , N/m^2	E , N/m^2	ν
Frames steel	2.4E8	3.6E8	2.1E11	0.3

Introduction of the models

In the present study, 6 models including a sample frame with castellated beams and rigid connection surrounding in concrete, the same frame surrounding in concrete, a sample frame with semi-rigid connection non-surrounding in concrete and a frame with semi-rigid connection surrounding in concrete all were exposed to the blast loads effect. Also, the rigid connection non-surrounding frame was under the cyclic load effect and the semi-rigid connection non-surrounding frame was under the cyclical load effect.



c) Rigid connection surrounding in concrete RCCSC
d) Semi-rigid non-surrounding in concrete RCC

Fig. 2. Different models used in software

For the steel frames the solid element (C3D8R) and for modeling concrete the same element was used. These elements are able to model cracking caused by tension and crush created by pressure. This element is defined via eight nods each of which has three transition degrees of freedom in three directions.

Description of characteristics of concrete materials:Concrete Damage Plasticity

In the concrete damage plasticity model, the concepts of Isotropic damaged elastic, tensile and the compressive plastic and non-linear behavior of concrete were applied. This model has the potential of being used in static and dynamical calculations.

Boundary conditions of the models

In all samples, degree of freedom is closed outside the boundary elements plate of the beam and columns. In the samples, concrete was defined, the connection between concrete and steel is defined via Penalty with a coefficient of friction 0.35. All transitional and rotational degrees of freedom are included in the level of basis of the column. Interaction between steel pieces with welding is defined with Tie. Other contacts between steel pieces without friction are defined with less friction. The model behavior under the blast loading effect was put under the dynamic explicit analysis and the yielding criterion is Von-Misses. The columns components of IPB280 and the beam CPE180 and cutting pattern of castellated beams pattern opening are a hexagon of Fig. 3. In order to reduce the model errors, the elements were selected as small as possible. The explosive loading in the form of lateral pressure was considered to be equal to 45kg TNT in 45m distance. This amount of explosives in the determined distance has a pressure of 5 MPa and the loading continuation is 0.085 seconds into the frame. The history charts of the explosive load are similar to Fig. 1.

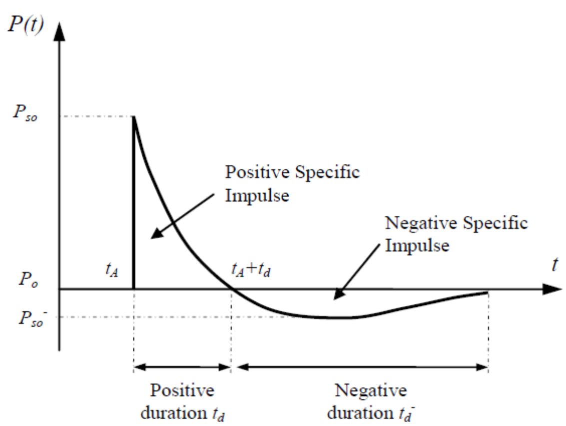
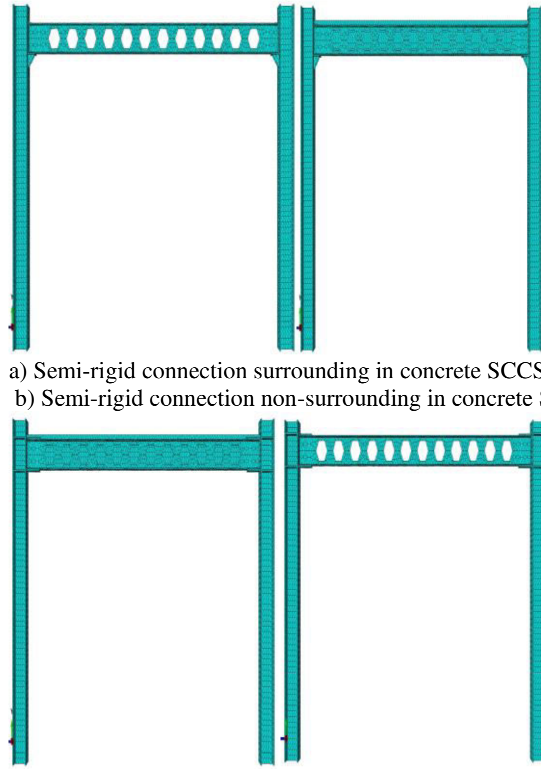


Fig. 1. Time history of blast load record



a) Semi-rigid connection surrounding in concrete SCCSC
b) Semi-rigid connection non-surrounding in concrete SCC

c) Rigid connection surrounding in concrete RCCSC
d) Semi-rigid non-surrounding in concrete RCC

Fig. 2. Different models used in software

Prediction of pressure resulting from explosion

In fact, all parameters related to explosion depend upon two independent parameters. One is rate of released energy at the time of explosion and the next one is the distance between centers of explosion to the blast waves site. The Destructive power of a bomb is computed according to these two important factors: Weight of explosive substances in TNT scale (W), and distance of explosive substances (R).

The result of these two quantities in form of the parameter Z (scaled distance) is described as follows:

(1)

In the equation above, R is in terms of meter and W is in terms of kilogram.

(2) $p_{so} = 0.975/z + 1.455/Z^2 + 5.85/Z^3 - 0.019 + \text{bar} \quad (0.1\text{bar} < p_{so} < 10bar)$

(3) $p_{so} = 6.7/Z^3 + 1bar \qquad (p_{so} > 10bar)$

Table 2. Characteristics of models

Samples Types	Samples Name	Frames height	Frames opening	Concrete thickness	Concrete height	Concrete thickness of samples
RCSF	RCC-QL	3	5	---	---	---
	RCC -BL	3	5	.30	0.32	.05
	RCCSC - BL	3	5	---	---	---
	RCCSC - BL-RP	3	5	.30	0.32	.05
RCSSF	SCCSC - BL	3	5	---	---	---
	SCC -BL	3	5	.30	0.32	.05

Table 3. Details of frame with tangle connection

Label	Length (mm)	Width (mm)	Thickness (mm)	Descriptions
IPB280 columns	3100	280	-	
CPE180 castellated beams	5000	91	0.8	
Upper plate of rigid connection	260 120	60	15	
Lower plate of rigid connection	260	130	15	
Continuation plates	24.4	134.75	15	
Full penetration to penetration weld	130 11	2		Weld Penetration
Fillet weld	ver.	7	7	4mmFillet Welds

Table 4. Details of frame with semi-tangle connection

Label	Length (mm)	Width (mm)	Thickness (mm)	Descriptions
IPB280 columns	3100	280	--------	
CPE180 castellated beams	5000	91	. 8	
Cornerstone 7 top of connection (equal wing)	260	70	7	
Lower plate of rigid connection	260	130	15	
Plate series	24.4	150	12	
Quater	130	120		Weld Penetration
Fillet weld	ver	7	7	4mmFillet Welds

Table 5. Characteristics of reinforcement concrete

Concrete				
E , N/m^2	**Thickness, m**	**ν**	**Cover up CPE180**	**Cover down CPE180**
2.04E10	.32	.2	.05	0

A second famous equation was introduced by Newmark and Hansen 1961.

$(4) p_{so} = 6784W/R^3 + 93(W/R^3)^{1/2}\text{bar}$

The equation for computing td is a logarithm as below:

$(5) \log_{10}\left(t_{d/W^{1/3}}\right) \approx -2.75 + 0.27 \log_{10}\left(R/W^{1/3}\right)(Z \geq 1.0)$

$(6) \log_{10}\left(t_{d/W^{1/3}}\right) \approx -2.75 + 1.95 \log_{10}\left(R/W^{1/3}\right)(Z \leq 1.0)$

Time history of pressure caused by explosion is defined via the Friedlander equation which is an exponential function.

$p_s(t) = p_0 + p_{so}(1 - t/t_d)\exp(-bt/t_d)(7)$

This load is widely applied on exterior view of the building, which is a curve and its value has a reverse ratio to the third power of the distance from the center of the explosion. But, in many cases for ease of use, the Ps(t) diagram is assumed in the form of a triangular load (i.e., the pressure is assumed to be linear with time) , where the initial pressure Pso reaches zero at time td. In addition, a wide load distribution is assumed to vary linearly in height. In some articles, this load is focused on each floor level. In the present study, the load is widely analyzed with linear distribution over time.

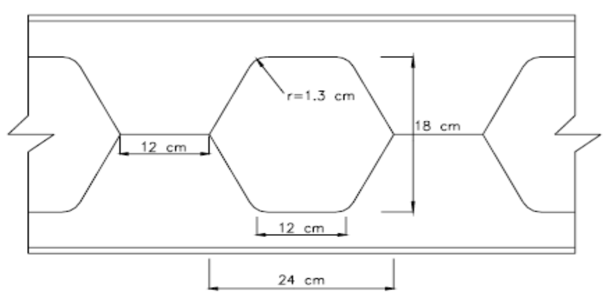
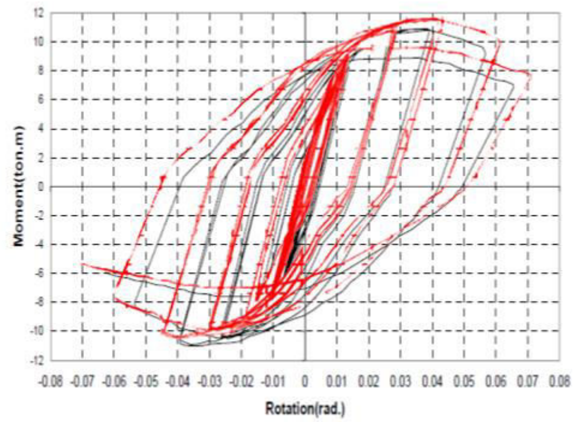


Fig. 3. Details of castellated beams cut modeled in software

Validation of models

In order to validate the models, first laboratory samples were modeled precisely. The results show accuracy of modeling in the present study. Fig. 4 Illustrates moment-rotation diagram of software model and comparing with the reference.



Examining the responses of frames with castellated beams

Castellated beams have 7 modes of failure as : Flexural failure,- lateral and torsion buckling of whole beam, virendeel failure, web connection failure, shear buckling (lateral - torsion) web beam, compressive buckling of web , and buckling pressure section (T) of beam shape and the eighth failure (Beam local buckling in the plastic zone at a relatively short distance between the connection plates until the first beam opening is concentrated) through conventional shift on top of the frame in the laboratory under the cyclic load was obtained via Manual ACT24.

Example #1:

Rigid Connection for Castellated Beam in Steel Frame under the seismic loads (cyclic)RCC-QL

In this study, a steel frame was modeled in software for verification and comparison and with the results of laboratory specimens was placed under cyclic load. Under this type of loading, another model of failure was added to the weak points of these types of beam. The first signs of submission emerged on the compression side of the beam and the outer surface of the flange, the first T shaped cross-section appeared after the connection site and

After that, the yielding area expanded to the inner surface of the flange and through extension towards the web cross-section (T) shaped, the opposite stretching area is yielded. Then the yielding develops to the compressible flange and stretching the first web after the connection area. After yielding of this area, the movement continues in the opposite direction and continues to the cross-section of second and third (T) shape after the connection area. At time of expansion of yielding in different areas of the beam, the loading procedure of the beam is ascending and no fall was observed in rate of load. But after stabilization of the yielding expansion and through increasing the rate of imposed rotation on the beam, the compressive flange of the first (T) shape cross-section was gradually ricochets and consequently the first web of the cross-section faced with compressive buckling. After occurrence of the buckling and development of transformations in the cross-section, the loading power of the beam was decreased and rate of transformations and plastic rotations were increased.

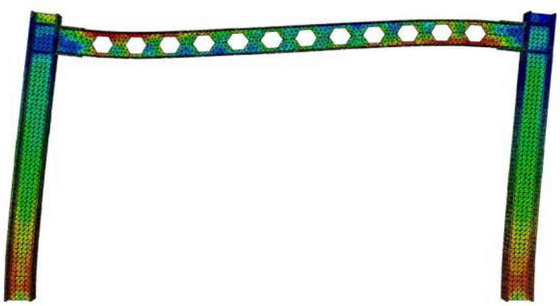


Fig. 5. Yielded points in the beam under cyclic load effect

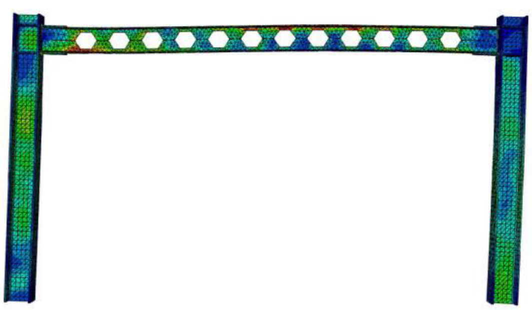


Fig.6. Yielded points in the beam under the explosion load effect

Example #2:

Rigid Connection with Concrete Surround for Castellated Beam in Steel Frame under explosion loads effect- RCCSC –BL

This model similar to the laboratory sample was put under the seismic load (cyclic); the same model undertook the blast load effect. The results indicated that the rate of stress in the castellated beams at the beginning of loading in blast load mode is higher (more) than cyclic load. But, during the loading time, cyclic load will impose more stress on the frame. In the blast loading, this model also showed a failure mode similar to the cyclic load, however, due to the nature of this load acting like a monotonic load and beginning of destruction occurs only in one flange, for instance, the bottom flange of the T shaped cross-section after the beam connection close to the explosion place Fig.7.

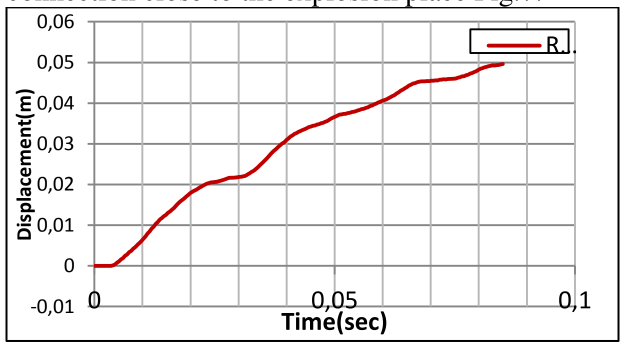


Fig. 7. Place-time displacement diagram of the steel frame with rigid castellated beams connection non-surrounding in concrete RCCBSF

Example #3:

Rigid Connection with Concrete Surrounding for Castellated Beam in Steel Frame-under the blast loads effect RCCSC-BL

When the castellated beam is surrounding in concrete, either the frame or the castellated beam shows a better performance. This is evident via comparing the place-time displacement diagram of the frame in two surrounding and non-surrounding in concrete modes. Displacement of the frame with the non- surrounding beam in concrete is approximately 5 times more than the frame with surrounding beam (Fig. 8).

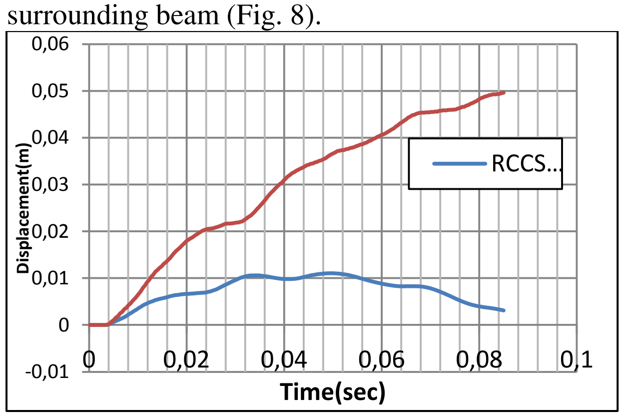


Fig. 8. Comparison of time-place displacement diagram of steel frame with rigid castellated beam connection surrounding in and non- surrounding in concrete

Example #4:

Semi-rigid Connection for non-surrounding in concrete Castellated Beam in Steel Frame

Under the explosion loads affect SCC -BL

The frame with semi-rigid castellated beam connection non-surrounding in concrete did not show an acceptable performance. The results show that the column flange in the connection place to angle experiences a local yielding, so it causes all capacities of the frame to remain unused Fig.9.

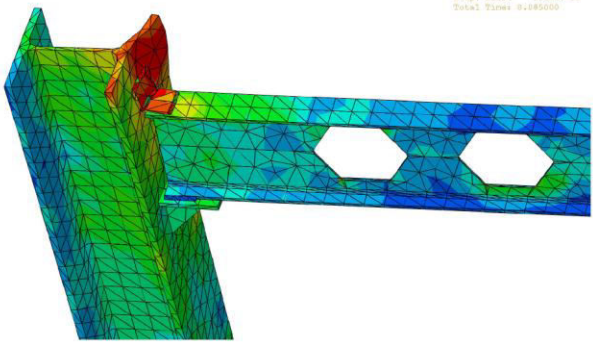


Fig. 9. Yielding stress and local buckling of column flange of frame with semi-rigid connection non-surrounding in concrete

Example #5

Semi-rigid Connection with Concrete Surround for Castellated Beam in Steel Frame -under the blast loads effect SCCSC -BL

Frame with semi-rigid castellated beams surrounding in concrete was place under the blast effect. The frame response like the maximum displacement of the frame and base shear during the loading time was drawn to be compared with other models.The rigid castellated beam connection surrounding in concrete undergoes higher base shear compared with castellated beam with non-surrounding rigid connection. This is because of being surrounded in concrete makes the frame more rigid and at the early moment when the most critical form of load is imposing, it imposes base shear on the rigid frame surrounding in concrete.

By comparing the displacement of the frame with semi-rigid connection surrounding in concrete with the rigid frame surrounding in concrete, it was realized that the semi-rigid frame shows less displacement compared with the rigid connection frame. The reason is for the local yielding of the column flange and semi-rigid connection angle which prohibits the frame to function properly and the frame can't use whole capacity against explosion.The castellated beams have 7 modes of failure which being surrounding in concrete helps the failure to be improved significantly. The most important of such failures are lateral – torsion buckling of whole beam and shear in welding shear of cutting pattern place. Fig.12 illustrates the rate of tension in welding of the cutting patterns place in both surrounded in and non-surrounding in concrete states of the castellated beam with rigid connection. Appropriate place for the insertion of Fig. 12

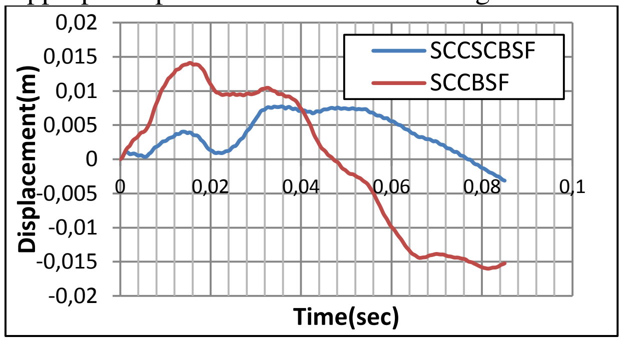


Fig. 10. Comparing time-place displacement of steel frame with semi-rigid castellated beam connection surrounding in and non-surrounding in concrete

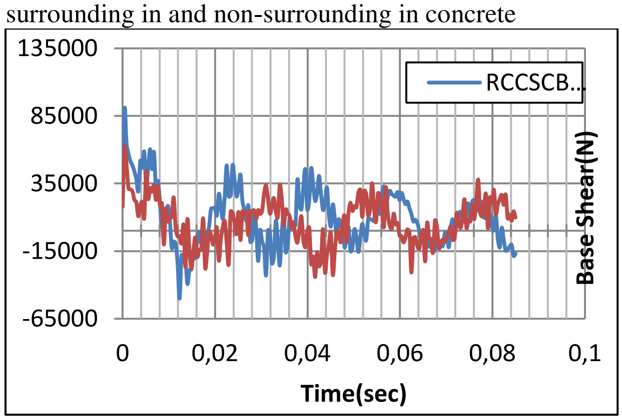


Fig. 11. Comparison of base-time shear of steel frame with semi-rigid castellated beam connection surrounding in and non-surrounding in concrete

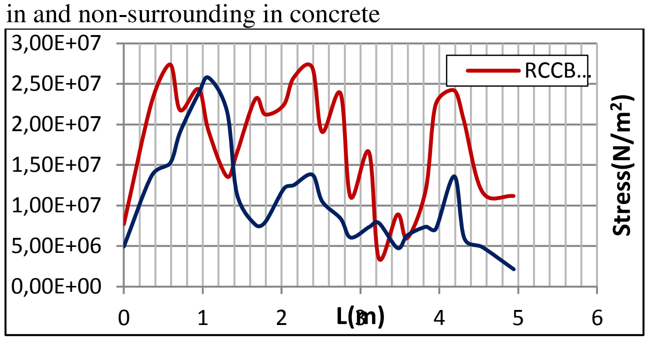


Fig. 12. Von-Misses stress in welding site of cutting patterns of castellated beams with rigid connection surrounding in and non-surrounding in concrete

Example #6:

Rigid Connection with Concrete Surround for Castellated Beam in Steel Frame with

reinforcement plate lower flange under the blast loads effect RCCSC -BL-RP

The eighth mode of failure of the castellated beam (local yielding in place of connection after the first opening of lower wing) which would not be improved at the beam buries in concrete. But, in some moments of blast loadings of the buried state, stress in the lower flange of the mean will increase. This stress can be reduced by adding a reinforcement plate to the lower flange.

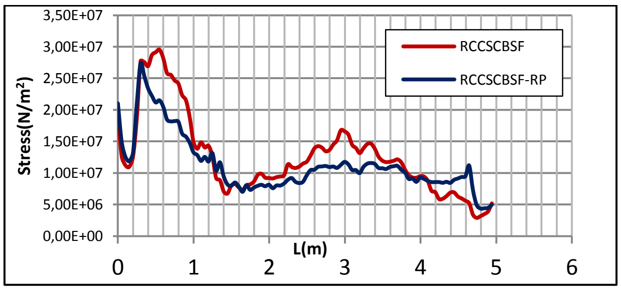


Fig. 13. Von Misses stress between lower flange and the web and over the castellated beam with rigid connection in two surrounding in and non-surrounding in concrete with and without reinforcement plate

Results and Discussion

In the present study, through analyzing the castellated beams frames under blast loads with rigid and semi-rigid connections and in both surrounding in and non-surrounding in concrete the following results were obtained:

Similar to the failure mode #8 resulted from the laboratory sample of thecastellated beam under cyclic loading, under the blast effect also in the same place (first T-shaped cross after connection) the beam experienced local yielding , except the lower flange of the beam (close to the blast site) this occurs.

Displacement of the frame with castellated beam having rigid connection non-surrounding in concrete was approximately 5 times greater than the frame non-surrounding in concrete.

On the castellated beam with rigid surrounded frame in concrete , in the early moments of blast loading which is the longest loading time, higher base shear was imposed compared with the non-surrounded frame in concrete.

In comparison with semi-rigid surrounded connection frame and rigid buried connection frame, it was observed that the semi-rigid frame shows less displacement versus the rigid connection. This is because of yielding of some part of column flange and semi-rigid connection angle causing local buckling of the column flange. So, the frame does not function properly and the frame fails to use all capacities against explosion.

The eighth mode of failure the castellated beam is local yielding of the first T-shaped section after connection to lower flange, which is not improved as the beam surrounding in concrete. But, sometimes explosive loading exceeds the non-surrounding state of tension in the lower flange that considerably decreases via addition of reinforcement sheer to the lower flange.

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NOTATION

SCCSC	Semi-rigid Connection with Concrete Surround for Castellated Beam in Steel Frame
RCCSC	Rigid Connection with Concrete Surround for Castellated Beam in Steel Frame
SCC	Semi-rigid Connection for Castellated Beam in Steel Frame
RCC	Rigid Connection for Castellated Beam in Steel Frame
RP	Reinforcement Plate
EQL	Earthquake Loads(Cyclic)
BL	Blast Loads
R	Stand-off distance
W	Charge Weight
Z	Scaled distance
P_{SO}^{+}	Positive peak Over Pressure
P_{SO}^{-}	Negative peak Over Pressure
P_0	Pressure of ambient
Pr	Reflected Pressure
t_A	Arrival Time
t_d	Duration of Pulse