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Comparison of Predicted and Experimental Behaviour of RC Slabs Subjected to Blast using SDOF Analysis

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ABSTRACT

Explosions emanating from terrorist attacks or military weapons cause damage to civilian and military facilities. Understanding the mechanical behaviour of reinforced concrete structures subjected to blast is of paramount importance for minimizing the possible blast damage. A full-scale experimental program consisting of six reinforced concrete slabs with compressive strengths of 60 MPa, 50 MPa and 40 MPa, measuring 1.0 m × 1.0 m × 0.08 m, and subjected to 2.7 kg of non-confined plastic bonded explosive, was conducted in blast test area of Science and Technology Aerospace Department (Brazilian Air Force). This paper compares experimentally measured peak displacement values with theoretical values. Theoretical analysis was carried out using single degree of freedom (SDOF) models. The comparison showed that SDOF analysis worked very well in predicting the reinforced concrete slab peak displacement against blast effects. Qualitative analysis after the experiments showed that the blast wave shape generated by the cylindrical explosive was not uniformly distributed on the slabs for the standoff distance of 0.927 m/kg$^{1/3}$.

Keywords: Blast test; Peak displacement; Single degree of freedom; Reinforced concrete

NOMENCLATURE

k	Stiffness (N/m)
m	Mass (kg)
PBX	Plastic bonded explosive
P_o	Peak pressure of blast load (MPa)
Pr	Reflected pressure of blast load (MPa)
Pso	Incident pressure (overpressure) (MPa)
R	Standoff distance (m)
R_d	Deformation response factor
T	Logarithm of Z (T=log Z)
t_d	Time duration of positive phase (s)
Tn	Natural period of vibration in (s)
u_0	Dynamic peak displacement (mm)
$(u_{st})_0$	Maximum static peak displacement (mm)
W	Equivalent TNT mass (kg)
ω_n	Natural frequency of vibration (rad/s)
Z	Scaled distance (m/kg$^{1/3}$)

1. INTRODUCTION

Explosions close to buildings have been common threats of extreme loading on structures around the world. Structural engineers have studied blast resistant design in order to mitigate its effects on structures[1–3]. Loads from blast wave can affect the performance of structures such as those made from reinforced concrete (RC), which is one of the common construction materials used to construct buildings and bridges around the world. Most of these structures have no protective structures and are not designed to resist blast loads. Public buildings need protections against blast[1] because of the many terrorist attacks that have occurred in the last century. Limiting collapses and reducing the loss of life are the objective, if the design cannot withstand the blast load. Even if structures designed for the effects of typical out-of-plane loadings (such as earthquakes) may have good lateral load carrying capacity[2], they may not perform well against blast loads depending on the explosive charge and the location of the charge in the building. These explosions generate dynamic loads against essential supporting structural elements, such as slabs, columns or beams. RC structures can be made as barrier or shelter just to support blast effects and avoid loss of people and assets[3]. Investigation of the resistance of concrete against blast loads is necessary not only for protective design of structures, but also for weapon systems developers.

An explosion is a sudden release of energy and can be classified as physical, nuclear or chemical, depending on the source[4,5]. This paper deals with chemical explosions, which are the result of exothermic chemical reactions. The sudden elevated temperature and pressure in the environment are the main factors that can cause damages to structures close to the explosion epicentre. The energy released travels toward all directions around the epicentre compressing the air and generating a front wave, called shock wave or blast wave[4,6,7], which has supersonic velocity.

Understanding the behaviour of structural elements and the whole structure for the effects of blast is important because these structures hold people and private or government assets. Since the second part of the last century the researches of blast loading on structures and its behaviour were growing[8-11].

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Lessons from many accidents, two World Wars and terrorist attacks contributed to this. Knowledge of blast wave parameters, and how the energy coming from the blast generates damage to structures, enable structural engineers to design RC structures efficiently incorporating short-duration dynamic load effects. Comparison of theoretical models and experimental results have been shown as an efficient method to validate experimental data from blast loads. Luccioni & Luege[12] showed that computing simulation could predict the diameter of a crater on the surface of a pavement made from RC very well when compared to experimental results. Zhao & Chen[13] conducted blast tests to verify the response of a 40 mm thick RC slab with 42 MPa having three different equivalent TNT mass and stand-off distance. They verified that the higher the TNT mass and the lower the standoff distance, the higher the recorded damage. Their results also pointed out that the response of concrete and reinforcement increase in resistance when subjected to blast due the dynamic increase factor. Li[14], *et al*. conducted a full-scale field test with two 40 MPa RC slabs and 5 ultra-high performance concrete (UHPC) of 145 MPa. The slab with UHPC had micro steel fibres measuring 15 mm in length and 0.12 mm in diameter. The explosive was positioned in contact to the upper face of the slabs and measured 0.1 kg and 1.0 kg of equivalent TNT. Slabs with UHPC had less damage than the slabs with normal RC. Diameter of perforation on the bottom surface of UHPC slabs were around 50 per cent smaller than the slabs with normal concrete.

Di Stasio[15] states that many agencies around the world have been concerned about losses in both peaceful times and during conflicts because of explosions close or in buildings. Several codes and standards have been published giving guidance for better constructions to resist blast wave as mentioned by DOD[3] and Campidelli[16], *et al*. to increase survival rates of structures and people after a blast event. These documents take into account the fact that structural elements have different behaviour under static and dynamic loads[17–19]. Structural dynamic response are different from static responses. There is a lack of information about statistical distribution of blast parameters in the literature[16]. This paper is a follow up of Mendonca[20], *et al*. and presents comparison of experimental and theoretical dynamic reinforced concrete slab response subjected to blast wave. Widely known equations of SDOF models, as outline in Rigby[21], *et al*., were used in this study. SDOF models are idealized representation that take into account one degree of freedom. The mass of the system is lumped at one point of the structure and the structure is assumed inextensible axially. Chopra[18] presents detailed explanation about the idealization of a structure as a SDOF system.

Full-scale tests with six RC slabs subjected to blast wave generated from non-confined explosives were the experimental data source used for comparison with the SDOF analysis. The research focus was on global response parameters such as peak displacement.

2. MATERIAL AND METHODS

To establish structural designs for mitigating the effect of blast, the blast overpressure and the respective load must be fully understood. After an explosion, the shock wave rises suddenly above the ambient pressure and shocks against the structures around the epicentre, generally causing damages. The main parameters of the shock wave are peak pressure, time duration of positive phase (t_d) and positive impulse. The peak value of the pressure is called incident peak pressure (Pso) or overpressure. Pso decays rapidly and oscillates around the ambient pressure before back to stability. However, when shock waves from an explosion hit the surface, the waves will be reflected and produce a pressure called reflected pressure (Pr) that amplifies the incident pressure, Pso. Air blast theory states that Pr is at least two times Pso[2]. The second peak pressure recorded was typically two times higher than the first peak pressure. The higher amplifying ratio is observed when the front wave angle of incidence is perpendicular to surface. The value of positive impulse is the area under the pressure time-history curve[5].

The shock wave formation pattern depends on the shape of the explosive. Warheads with cylindrical format and triggered in one side of the cylinder develop a pattern similar to what is shown in Fig. 1. Targets close to the base of the cylinder can suffer higher damages due to the shock wave shape. It is not uniformly distributed over the target for scaled distances lower than 1.2 m/kg$^{1/3}$ as described by Campidelli[16], *et al*.

Prediction of Pso, Pr and t_d for chemical and nuclear explosion can be determined by calculating the scaled distance (Z)[22]. This parameter depends on the standoff distance (R) in meters and the equivalent TNT mass of the explosive (W) in kg, as shown in Eqn. (1).

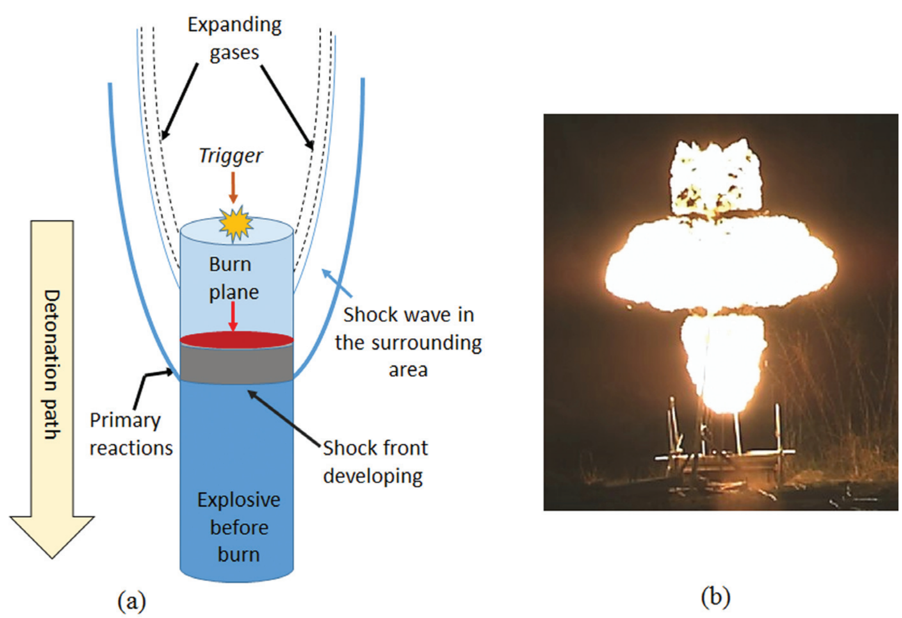

Figure 1. (a) Typical pattern of development of cylindrical shape explosive detonation. (b) Detonation of a cylindrical shape explosive triggered on top. Image 1.6 ms after trigger.

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

There are many equations available in literature to predict Pso[4]. Eqns. (2) and (3) of Kingery and Bulmash[23, 24] are widely used for predictions of Pso and Eqn. (4) to predict Pr. To get the value of pressure, it is necessary to determine the value of U beforehand using T, which is the function of the logarithm of Z ($T = \log Z$).

$$\begin{aligned} Pso &= 2.611 - 1.690\,U + 0.008\,U^2 \\ &\quad + 0.336\,U^3 - 0.005\,U^4 - 0.080\,U^5 \\ &\quad - 0.004\,U^6 + 0.007\,U^7 + 0.0007\,U^8 \end{aligned} \tag{2}$$

$$U = -0.214 + 1.350\,T \tag{3}$$

$$\begin{aligned} Pr &= 3.229 - 2.214\,U + 0.035\,U^2 + 0.657\,U^3 \\ &\quad + 0.014\,U^4 - 0.243\,U^5 - 0.015\,U^6 \\ &\quad + 0.049\,U^7 + 0.002\,U^8 - 0.003\,U^9 \end{aligned} \tag{4}$$

Time of duration of blast load positive phase (t_d) is an important parameter for blast wave analysis. The Eqn. (5) of Kinney and Graham[22] is widely used in the literature for predicting of t_d.

$$\frac{t_d}{W^{\frac{1}{3}}} = \frac{980\left[1+\left(\frac{Z}{0.54}\right)^{10}\right]}{\left[1+\left(\frac{Z}{0.02}\right)^{3}\right]\times\left[1+\left(\frac{Z}{0.74}\right)^{6}\right]\times\sqrt{\left[1+\left(\frac{Z}{6.9}\right)^{2}\right]}} \tag{5}$$

2.1 Simplified Dynamic Response Analysis

The main difference between static load and dynamic load on structures is the time duration of the load. For dynamic loads, t_d is measured in milliseconds. Therefore, the material behaviour is different for each type of load. Concrete and steel increase in strength when subjected to dynamic loads. The dynamic increase factor (DIF) characterizes this effect. The value of DIF for the concrete is about 20 per cent and for steel is about 10 per cent[2,25]. Challenges regarding the accurate determination of the dynamic behaviour of structures under blast event has been reported in literature[3,16,20]. The establishment of design procedures for damages preventing in structures and loss of human lives reducing are the main objectives of these documents. The shockwave parameters and RC slab responses have been reported using statistical or qualitative analysis[26].

Each structure with an assumed single degree of freedom has a natural period of vibration (T_n) as shown in Eqn. (6)[25]. The structure has a natural frequency that depends on its stiffness (k) and mass (m) as shown in Eqn. (7).

$$T_n = \frac{2\pi}{\omega_n} \tag{6}$$

$$\omega_n = \sqrt{\frac{k}{m}} \tag{7}$$

Maximum static peak displacement $(u_{st})_0$ can be used to determine the maximum dynamic peak displacement (u_0), from the maximum peak of the blast load (P_0), as shown in Eqn (8).

$$(u_{st})_0 = \frac{P_0}{k} \tag{8}$$

Deformation response factor (R_d) is applied to determine the final value of dynamic peak displacement, as Eqn (9).

$$u_0 = R_d\,(u_{st})_0 \tag{9}$$

The R_d value can be determined from the curve of the shock spectra for triangular pulse (Fig. 2) and depends on the time of duration of blast load positive phase and natural period of vibration.

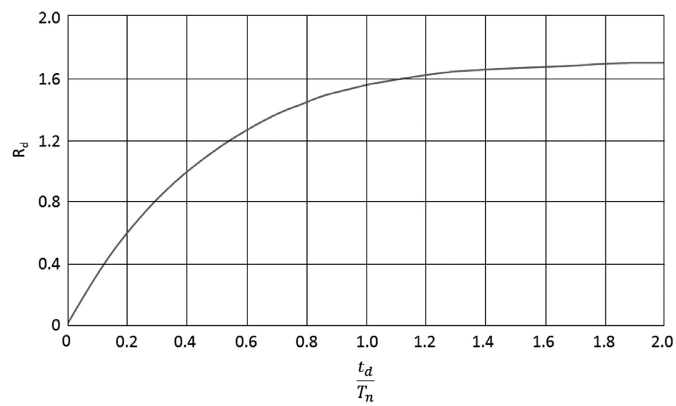

Figure 2. Shock spectra for triangular pulse.

2.2 Setup for Experimental Test

Six slabs having two different reinforced concrete design with dimensions of 1.0 × 1.0 × 0.08 m were subjected to blast in a field test program. Three slabs with 60 MPa of concrete compressive strength and reinforcement ratio of 0.25 per cent in two ways. Two slabs with 50 MPa of concrete compressive strength and 0.175 per cent of reinforcement ratio in one direction and 0.37 per cent in the perpendicular direction. Reinforcement was positioned in the bottom face of the slab to carry positive moment during the blast load. Tensile strength for the reinforcement was estimated as 350 MPa. Tensile strength of concrete was estimated about 10 per cent of compressive strength. The slabs were simply supported on two sides and the explosive was suspended in 2.0 m above. Scaled distance for the tests was 1.4 m/kg$^{1/3}$. Non-confined cylindrical PBX explosive, measuring 20 cm in high and 10.5 cm in diameter, was triggered by an electrical fuze on top of the cylinder. Eight pressure sensors were positioned at 2.0 m from the explosive. The record rate of the sensors is 0.01 ms that allows plotting a reasonable pressure time-history curve considering the predicted t_d. Plastic non-confined explosives have been widely used for blast tests to measure blast wave effects[20,27]. The main reason is that records from blast effects are more reliable when there are no explosive fragments.

To verify the development of the shape pattern of a cylindrical explosive, one slab with 40 MPa (labelled slab A) was subjected to a blast test with a scaled distance lower than 1.2 m/kg$^{1/3}$. The configuration of this slab was reinforcement ratio of 0.175 per cent in both directions and scaled distance of 0.927 m/kg$^{1/3}$. Table 1 shows scaled distance for the tests and slabs design details.

Table 1. Configuration of the tests

Slab	Weight (kg)	TNT mass - W (kg)	R (m)	Z (m/kg$^{1/3}$)	Concrete (MPa)	Reinforcement ratio (%) – Two directions
1	180	2.71	2.0	1.43	50	0.175 and 0.37
2	175	2.69	2.0	1.43	60	0.25 and 0.25
3	175	2.58	2.0	1.45	50	0.175 and 0.37
4	170	2.60	2.0	1.45	60	0.25 and 0.25
5	155	2.72	2.0	1.43	60	0.25 and 0.25
A	170	2.76	1.3	0.927	40	0.175 and 0.175

Figure 3 shows the setup for the test, where the explosive is suspended above the slab at a standoff distance of *R*, the slab on the right position before test, the box where the displacement meters were sheltered under the slab and the pressure sensors positioned around the explosive with a distance of *R* from the explosive. The different position of the pressure sensors were used to verify if sensors close to the slab could record *Pr* in a better way.

Displacement meters were used to measure the displacement of the slab in mm due to the blast waves. The recording rate was 0.42 ms and the gages were attached to the bottom surface of the slab by a wire emanating from a potentiometer that records the upward or downward movement of the wire during the explosion. The potentiometer was placed in a metallic box to protect it from the blast wave and surrounding debris. A hook was pasted on the lower surface of the slab near the mid-span using a two-part epoxy resin. The hook was needed to hold the wire in place. Two hooks with two potentiometers were attached to increase the likelihood of data collection in case there is a failure during the experiment.

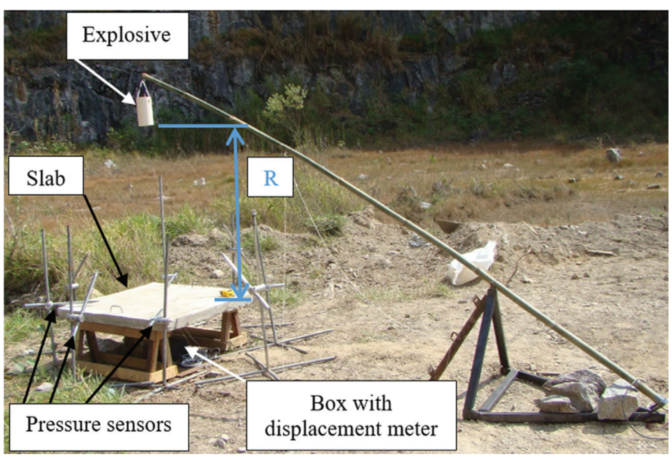

Figure 3. Test setup.

3. RESULTS AND DISCUSSION

Explosions near structures, such as the case in this experimental test, will produce a reflected pressure (*Pr*). Figure 4 shows the pattern of circular cracks developed on slab A upper surface. It was clear that the spherical wave formation is achieved for this test when *Z* is 0.927 m/kg$^{1/3}$. For the scaled distance of 0.927 m/kg$^{1/3}$, the shock wave was not uniformly distributed.

The pressure sensors recorded peak overpressure and reflected pressure. Sensors close to the slab could record peak values of *Pr* with less interference than sensors in the upper position. The displacement meter recorded peaks displacement of the slabs and can be seen in Fig. 5 (displacement-time history). The first peak of displacement was 18.74 mm and the second downward movement was 50.41 mm in total. Predicted displacement values were obtained from the structural dynamics equations. The highest peak was compared to predicted u_0 with P_0 represented by the reflected pressure given by Eqn. (4) and is dependent on the *Z* value. Eqn. (5) gave predicted time duration. *Pr* recorded by pressure sensors was used to calculate u_0 and was compared to u_0 measured by the displacement meter.

Figure 6 shows the comparison of u_0 predicted with u_0 recorded. It is worth to note that predicted values (first column), calculated with theoretical *Z* and t_d, for all slabs were higher than the experimental recorded values. The difference was in the range from 14 per cent to 60 per cent. Although values

Figure 4. Slab A post-test. Circular cracks were developed on the upper surface.

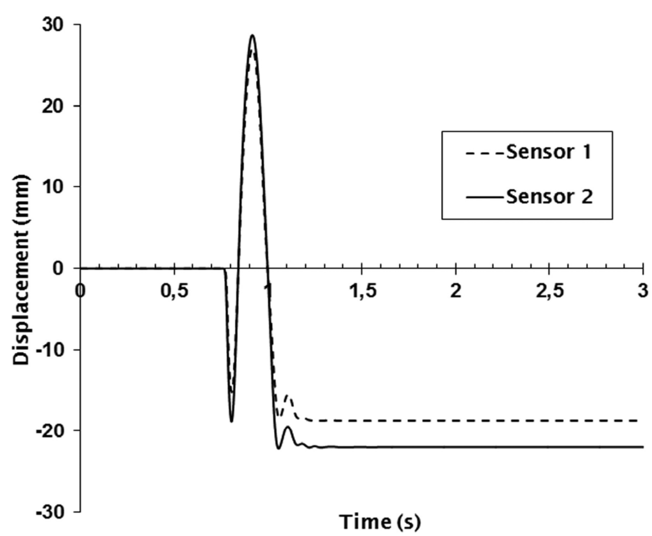

Figure 5. Record of displacement meter of slab 2.

for predicted u_0, considering the reflected pressure recorded by pressure sensors (third column), are also higher, the difference is less in this case, around 20 per cent higher. The response of the concrete slabs is governed by reflected pressure due the short standoff distance. The theoretical t_d value was higher than the observed t_d in the time-history curves generated from the pressure sensors records.

Equations for dynamic analysis worked well in predicting values of maximum displacement. Using the same equations but with recorded values of *Pr* and t_d the results were better, as can be seen when comparing the second and the third columns of the graph. The difference was 18 per cent to 28 per cent.

The difference shown in the results of predicted and recorded values can be attributed to the slab support conditions. The slabs were not fixed in the field-testing, but simply supported on two sides. Due to this, the slabs could move up and down giving a lower value of recorded displacement. In a finite plate, similar to the slab used in the test, blast wave generates waves at the edges of the slab, which will move toward the centre and can decrease the value of reflected pressure by clearing effect.

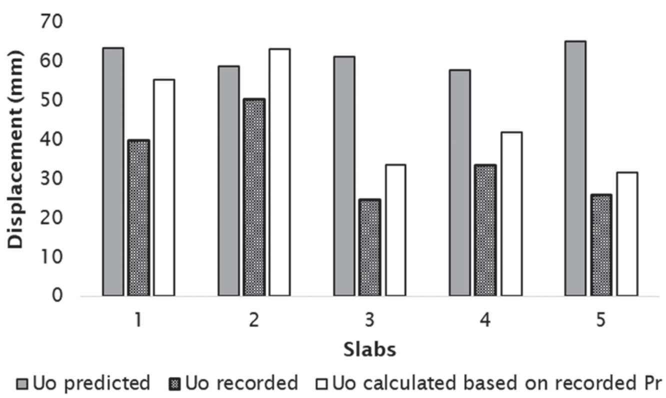

Figure 6. Comparison of predicted and recorded maximum displacement with predicted values.

4. CONCLUSIONS

Displacements of the mid-span of the five reinforced concrete slabs subjected to blast were verified by comparing experimental and predicted values. Qualitative analysis was done with the shape pattern of blast that shocked the sixth slab. Three of the slabs had 60 MPa compressive strength and 0.25 per cent reinforcement ratio in two way, two slabs with 50 MPa compressive strength having 0.175 per cent reinforcement ratio in one direction and 0.37 per cent in the perpendicular direction and one slab with 40 MPa compressive strength and 0.175 per cent reinforcement ratio in two way. The last slab was subjected to an explosion of the same explosive weight with a small scaled distance, 0.927 m/kg$^{1/3}$. All the slabs were simply supported and subjected to an explosion from a non-confined plastic explosive suspended at a standoff distance of 2.0 m (slabs with 60 MPa and 50 MPa) and 1.3 m (slab with 40 MPa).

The dynamic load analysis yields reasonable displacement and pressure values when compared to experimental tests. For displacement, the higher difference was 28 per cent for slab 1 and the lowest was 18 per cent for slab 5. The higher difference between predicted and recorded *Pr* was 50 per cent for slab 5 and the lowest was 1 per cent for slab 2. Kingery and Bulmash equations worked very well for predicting values of incident pressure and reflected pressure. The range of *Pr* variation is in good agreement with results reported in literature[2]. The prediction of the duration of time worked better when using the Kinney and Graham equation for t_d. However, recorded values of t_d were about one-half of the predicted value. It was due the small standoff distance of the explosive and the finite plate as a target. Since the deformation response factor from the spectra is a function of t_d, it has an impact on the predicted displacement. The maximum displacement prediction using SDOF analysis was 28 per cent when compared to the experimental results. Qualitative analysis showed that blast wave originated from a cylindrical charge of non-confined plastic bonded explosive develops a shape that is not uniformly distributed with Z = 0.927 m/kg$^{1/3}$.

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His contribution to the current study include setup preparation, overall approach, field test and full paper preparation.

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He has contributed in the methodology used to compare data and analysis of estimated values for the current study and the conclusion.

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He has contributed towards the design of test setup, analysis of experimental tests and estimated values for the current study.

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She has contributed with analysis of experimental tests in the current study.

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His contribution in this study is overall guidance during the work and conclusion through results.