Impact Detection in Composite Panel using Polynomial Model and aAgorithm

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***Abstract*—Polymer matrix composite materials are brittle in nature. Post-impact residual strength of composites can be much lower than the pristine structure, particularly in compression. This is because, when a composite plate or structure is subjected to impact it undergoes delaminations and /or disbonds. Often these interlaminar damages cannot be seen from outside during visual inspection of structure. This behavior poses a considerable worry for composite structural designers since they have to assume that any visually 'healthy' structure can potentially have delaminations or disbonds which are hidden in its interior. To prevent unexpected failure, primary aircraft structures are inspected regularly. Such inspections are mostly visual and time consuming. Hence it is of interest to develop an impact monitoring system which can help in determining the occurrence of an impact event on the structure when on ground or tarmac.**

This study attempts to develop a method to detect impact force using strain measurements during impact events. Impact tests are conducted using a portable drop tower where impact energy can be adjusted by changing the drop height. System identification technique is used detect the impact force and location of impact.

Keywords—Composite Panel , CFRP, ARMAX, structural health monitoring,algorithm, system identification

I. INTRODUCTION

A composite material is combination of two or more materials which are combined macroscopically that result in better properties than those of the individual components. Fibre-reinforced plastic is a composite material made of a polymer matrix reinforced with fibres. Usually fibers are carbon, aramid, glass, boron. Rarely, other fibres such as paper or wood or asbestos have been used. FRPs are commonly used in the aerospace, automotive, marine, ballistic Armor and construction industries. If carbon fibers are used then composite is called CFRP(carbon fiber-reinforced plastic) [1].

In mechanics, an impact is a high force or shock applied over a short time period when two or more bodies collide. Impacts of foreign objects on composite structures can create internal damage that reduces the strength of the structure significantly. However, the dent due to such impacts can be so small that it can go unnoticed during visual inspections. Such damages are called Barely Visible Impact Damage (BVID) and are a cause of worry for composite designers. Polymer matrix composite materials are brittle in nature. Post impact residual strength of composites can be much lower than the pristine structure, particularly in compression. This is because, when a composite plate is subjected to impact, it can suffer delaminations and/or disbonds.

The study of such impacts requires understanding the dynamics of the event, predicting the extent of the induced damage, and estimating the residual properties of the structure [2] [3] [4]. Impact damage detection can be done directly by using NDT techniques but if the location of impact is not known then, NDT has to be conducted for the entire structure, which is time consuming and expensive.

The objective of this project is to estimate the location and severity of impact event on a composite stiffened skin panel. The panel under consideration has resistance strain gauge sensors bonded to its stiffeners and strains from these sensors during impact event are recorded. The goal is to use this data to predict impact location and impact force.

II. METHODOLOGY

A. *Experimental set up*

For the present study, the composite panels were fabricated, shown in Fig. 1. Size of the panel is 940mm x 600mm. Panel is clamped to fixture using bolt and nuts. Hence actual size of the impacting area measures 820mm x 480mm. Skin of the panel is 3mm think and stiffener is of 2.4mm thick.

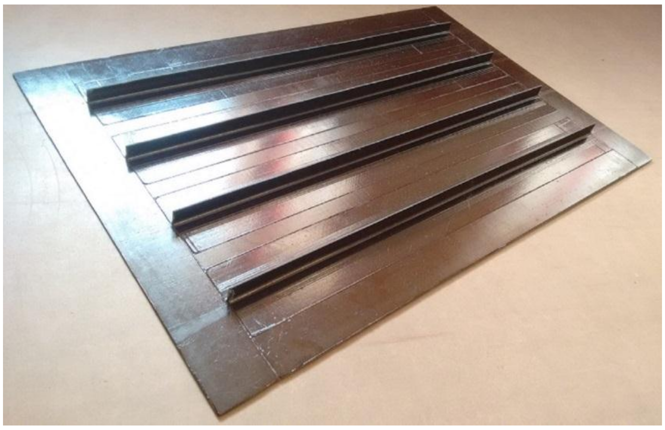

Fig. 1. Composite test panel

The composite panel described was impacted at different locations using impactor. The measurements of impact force and strains at various points were recorded continuously with a data acquisition system at 100-kHz frequency. Strains were measured using Resistance Strain Gauges (RSG). Impact

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force is measured using piezoelectric load cell as shown in Fig. 2.

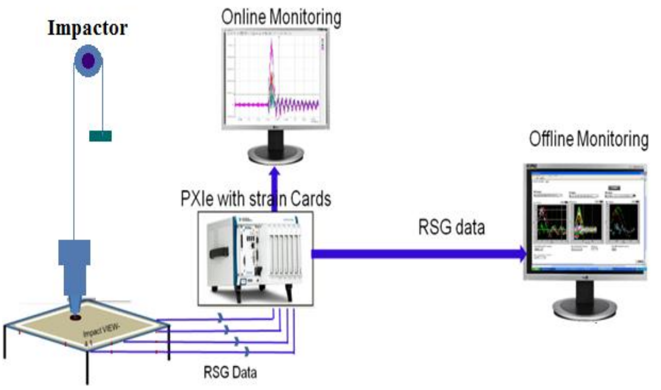

Fig. 2. Test arrangement

Strain gauges are bonded to the web of the stringer on one side. Each stringer is bonded with 3 strain gauges at 330mm spacing. In our panel we bonded 12 strain gauges as shown in Error! Reference source not found.**.(RSG location). During** simulation data acquired from strain gauges are used to create the polynomial ARMAX models.

Co-ordinates of impact locations for determining the parameters of the ARMAX models are shown in **Error! Reference source not found.**. Each ARMAX model describes the relationship between impact force at a given impact location (model input) and strain at a particular strain gage location (model output). Nine impact locations (3 on each bay) and 12 strain gage locations are considered in this project shown in

Fig. 3. ARMAX model generated locations and RSG locations

. Hence, a total of 108 ARMAX models were generated. Detail of the models and the approach to create them using system identification technique is explained later. In this project about 74 additional impact tests (validation cases) are considered along the 5 different lines of ‘Y’-coordinates namely Y=95,160,240,300,365 as shown in

Fig. 3. ARMAX model generated locations and RSG locations

, with different X-co-ordinates. Y=95,240 and 365 are model location lines, whereas 160 and 300 are very close to the stringer web.

Table 1: Co-ordinates of Impact location where ARMAX models where created

Impact location	X	Y
1	95	95
2	395	95
3	695	95
4	80	240
5	420	240
6	770	240
7	95	365
8	395	365
9	695	365

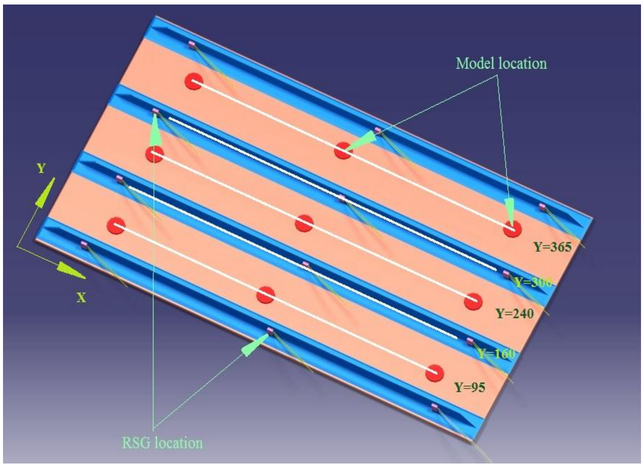

Fig. 3. ARMAX model generated locations and RSG locations

B. System identification

System identification is the art and science of building mathematical models of dynamic systems from observed input-output data. It can be seen as the interface between the real world of applications and the mathematical world of control theory and model abstractions. Constructing models from observed data is a fundamental element in science [[7]].

In this project all simulations are done by using system identification toolbox of MATLAB software.

In the system identification toolbox we used ARMAX structure to create polynomial models. It estimates polynomial model using time domain data. The syntax of ARMAX model is given below

M = armax(Z, [na nb nc nk])

This estimates an ARMAX model, M, represented by the following mathematical equation:

Equation 1: ARMAX equation

$$A(q)\, y(t) = B(q)\, u(t-nk) + C(q)\, e(t) \qquad (1)$$

Where:

na = order of A polynomial (Ny-by-Ny matrix)

nb = order of B polynomial + 1 (Ny-by-Nu matrix)

nc = order of C polynomial (Ny-by-1 matrix)

nk = input delay (in number of samples, Ny-by-Nu entries)

(Nu = number of inputs; Ny = number of outputs)

The estimated model, M, is delivered as an idpoly object (idpoly creates a model object containing parameters that describe the general input output model structure). M contains the estimated values for A, B, and C polynomials along with their covariances and structure information.

C. Response calculation using ARMAX model

Here, we present only with the algorithm for estimation of impact force (as a function of time) based on measured strain gage data. It is assumed here that impact location is known. The algorithm for estimating impact location is presented later.

The algorithm for impact force estimation works on the following principle. The impact is assumed to occur at one of the 9 locations where the system models are already available / generated. At any given instant of time, the impact force is assumed and the strains in the 12 gages are calculated by

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using the corresponding 12 ARMAX models. These calculated strains are then compared with actual measured strains at the same instant and a single scalar error measure is derived as shown in equation (2). The estimated impact force is then calculated by minimizing this scalar error measure. This minimization / optimization problem is not solved using conventional optimization techniques. Instead, the linearity property of the ARMAX model is leveraged – that is, impact force (input of linear dynamic system) and calculated strain (output of linear dynamic system) are linearly related. Hence, the scalar error measure (which is taken as the sum of error squares) is related to the impact force through a quadratic relationship. Finding the minima of this quadratic curve (parabola) is easily achieved through simple calculus based approach, which is shown in Fig. 4. This way the impact force that minimizes the scalar error measure is estimated easily and is computationally very efficient. The mathematical equations for the above explained operations are given below in equation (2), (3) & (4). Impact force has to be fed as input to all 12 ARMAX models to determine the calculated strains from each of the 12 strain gages. At first this is achieved in this project by using the Matlab in-built program called 'sim'. It was found that Matlab inbuilt code 'sim' was taking too much time for simulation. To reduce the time, and to obtain results close to real time, we developed a code similar to 'sim' and called it as 'sim_n. 'sim_n' does a same operation as in-built code 'sim'. However, unlike the Matlab in-built code 'sim', 'sim_n' computes only the output of ARMAX polynomial model while taking impact force as input.

Equation 2: Scalar error measure

$$\text{scalar error measure} = \sum_{S=1}^{S=12} (CS_S - TS_S)^2 \qquad (2)$$

Where,

CS= Strain calculated during simulation.

TS= Strain obtained by test data

S = strain gauge (Ex: S=4 corresponds to strain gage named S4)

Equation 3: Equation of parabola

$$y = aX^2 + bx + c \qquad (3)$$

Where y = Scalar error measure

x = Assumed force

a, b & c are the coefficients of the quadratic function.

Equation 4: Minimum of parabola to find minimum force

$$\text{Minimum force} = -b / (2*a) \qquad (4)$$

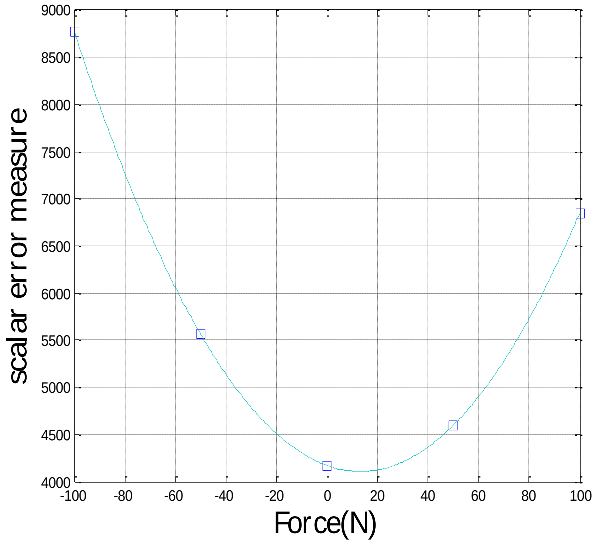

Fig. 4. Scalar error measure vs. Force – parabolic relationship

The graph of force results, obtained by test and by estimation, using 'sim_n' and algorithm at one of the location (420,240) for 9J impact energy is shown in Fig. 5.

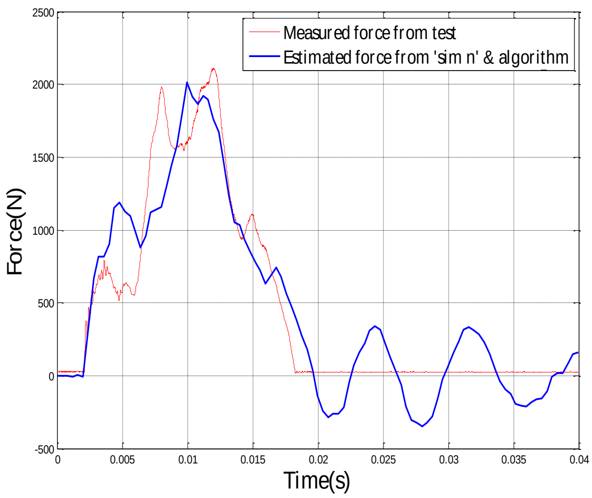

Fig. 5. Comparison of force between results obtained by test and by algorithm (420,240 9J)

D. Determination of impact force and location

In order to estimate impact location, firstly, a scalar term called 'Cumulative Error Measure (CEM)' is defined below. This parameter is calculated using strain data from all 12 gages and using a set of 12 ARMAX models from a chosen model location. Hence, CEM is dependent on the choice of the model location. The model location which yields the lowest CEM for a given strain dataset usually (but not always) provides a good initial estimate of impact location.

CEM calculation:

- At time instant 't_i', impact force 'F_i' is assumed.
- Use 'F_i' as input for a set of 12 ARMAX models from a chosen model location.
- Calculate strains in all 12 sensors due to 'F_i'.

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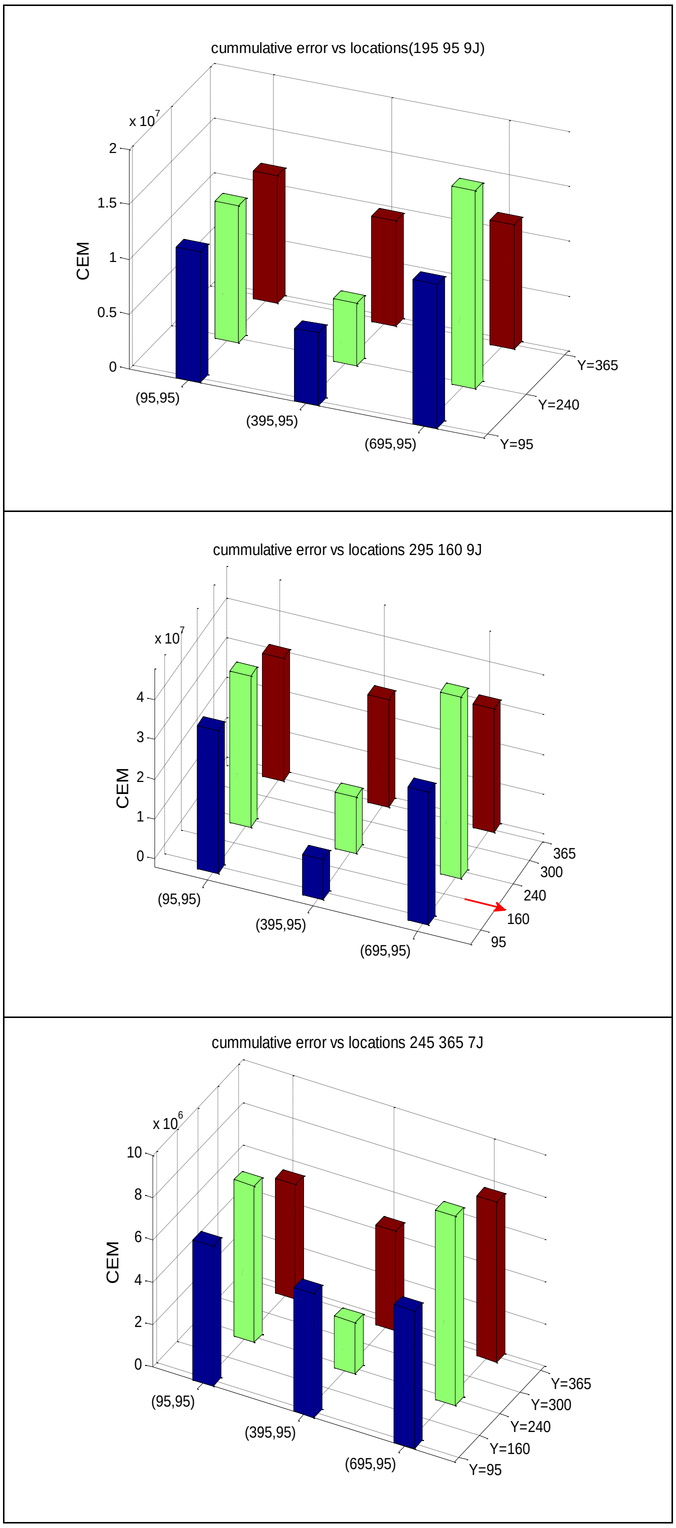


- Compare these strains with measured strain and calculate the scalar error measure as described earlier.
- Optimize ‘F_i’ to minimize the scalar error measure and then calculate cumulative error measure (CEM) which is the summation over the entire time interval.

Equation 5: Cumulative error measure

$$CEM = \sum_{i=1}^{N} \text{min scalar error measure} \quad (5)$$

Where N= Number of segments of time which is done during coding

Minimum scalar error measure can be found from Fig. **4**,Using equation (6).

Equation 6: Minimum scalar error measure

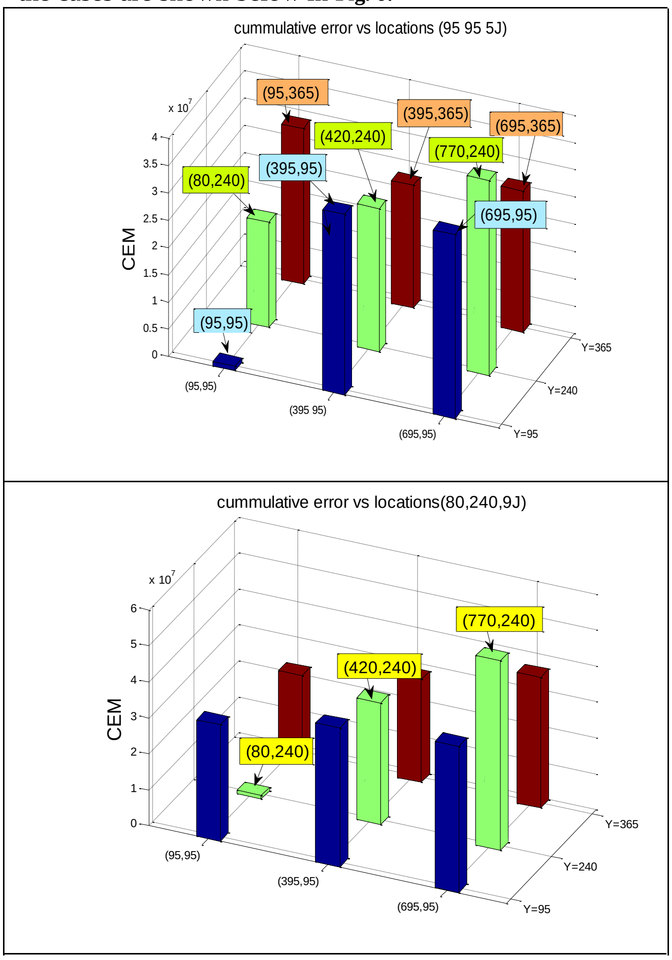
$$\text{min scalar error measure} = (-b^2 / (4*a)) + c \quad (6)$$

Where a, b and c are co-efficient of quadratic/ parabolic function obtained by quadratic curve shown in Fig. **4**.

- Repeat all the above steps for all 9 model locations to obtain CEM at all model locations.

To determine the location of impact 74 cases were considered. As a first step, locations where models were generated are only considered and CEM is calculated. CEM depends on scalar error measure which in turn depends on strain data. CEM also depends on choice of the model location. Hence the model location which is close to the impact location yields low CEM values.

It is found that cumulative error measure is minimum/lowest at the location where impact occurred in all cases. Some of the cases are shown below in **Fig. 6**.



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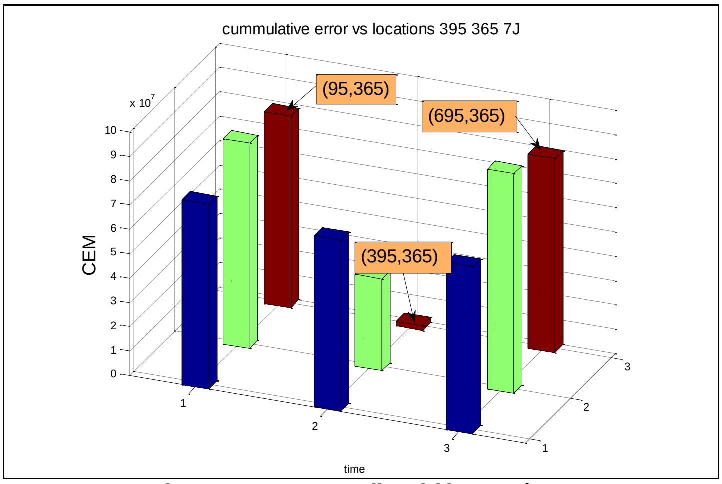


Fig. 6. Cumulative error measure at all model location for impact at a particular model point

E. Determining CEM for impact at locations other than the model locations

In this section, impact locations other than the model locations are considered. For each of these impacts CEM is found at all model locations. It is found that cumulative error measure is minimum at the model locations close to the impact location. Some of the cases are shown in Figure 7.

Fig. 7. Cumulative error measure at all model location for impact at point other than the model point

From Figure 7, we can see that each time while calculating 'CEM', it is found low at the mid location. This may be happened due to better models at the location or due to structural behavior. In order to nullify this effect and to find a better estimate for the impact location, Quadrilateral approach was attempted.

F. Quadrilateral approach

In the Quadrilateral approach, cumulative error measure (CEM) is calculated for a given impact data at all 9 model locations. These 9 model locations are joined by imaginary straight lines to form 4 quadrilaterals and they are named as quadrants (1, 2, 3 and 4) as shown in Fig. Each vertex of these quadrilaterals is a model location. Hence it has a 'CEM' value at the vertex for a particular impact. Therefore, each quadrilateral has 4 'CEM' values. These 4 'CEM' values are added to get the 'CEM sum' of the particular quadrant. The quadrant with least 'CEM sum' is considered as the region inside which impact is estimated to have occurred. In this approach, the impact location is reported as the centroid of the quadrilateral with least 'CEM sum'.

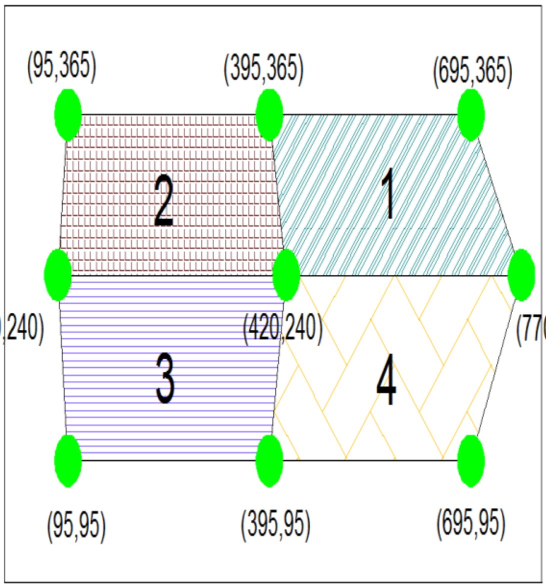


Fig. 8. Four quadrilaterals formed by 9 model locations.

Results:

This approach is applied for 74 cases of impact with different energies (varying from 5J to 12J) at different locations for different energies. Error in the location predicted compared to actual location in each case is shown in Fig. 9.

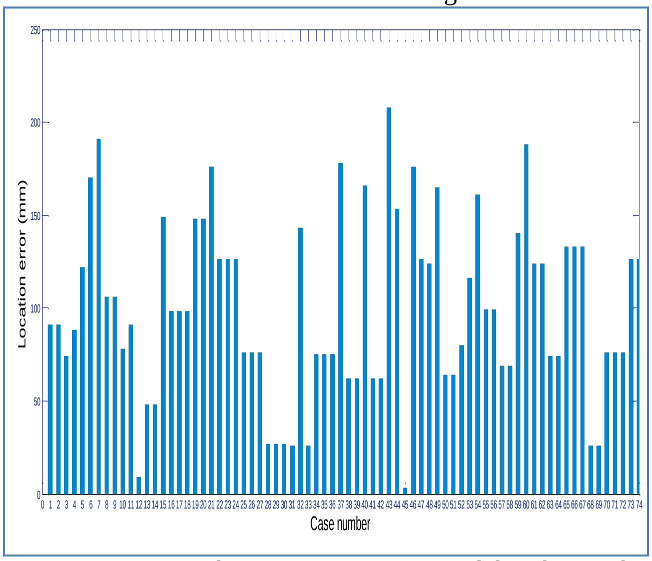
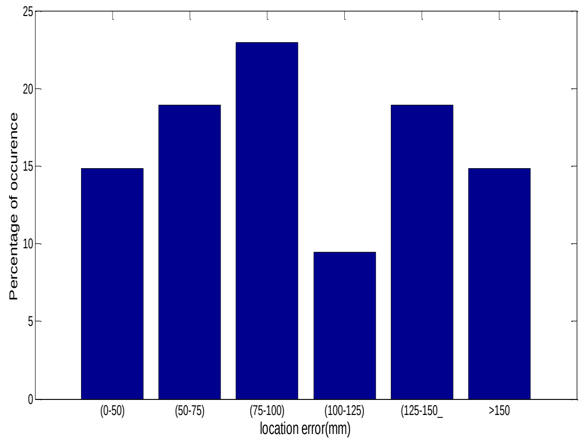


Fig. 9. Error in impact location estimation using Quadrilateral approach

Results show that in almost 60% cases the error is less than 100mm



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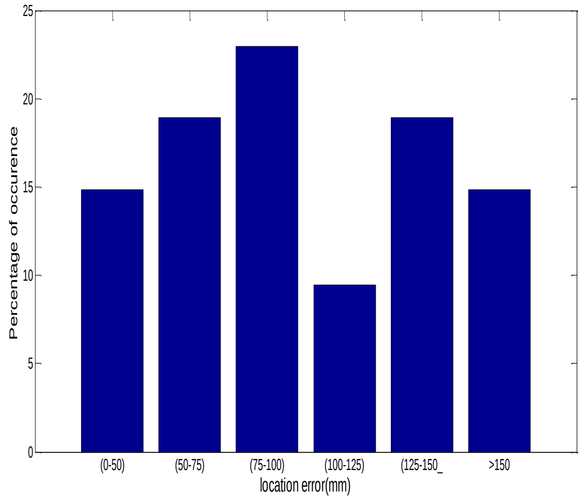

Fig0.) and only 15% of results showed error more than 150mm.

The ARMAX models generated can also be used with better algorithms for finding the impact location.

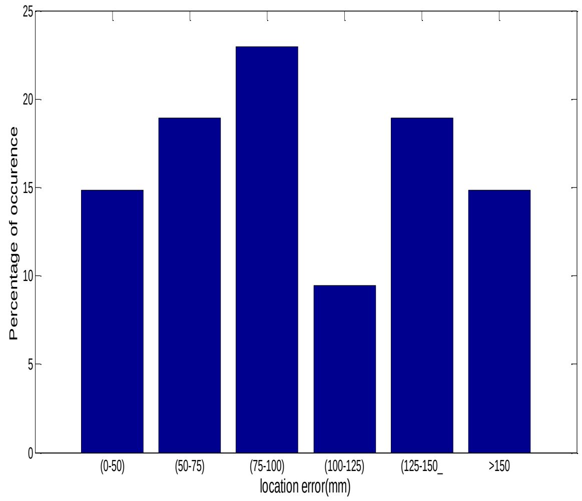

Fig. 10. Percentage of occurrence vs. location error for quadrilateral approach

III. CONCLUSION

This project deals with detection of low velocity impact event on a composite aircraft structure. Low velocity impact events such as tool drops typically occur during assembly/Operations/maintenance. Other sources of impacts are runway debris and ground vehicle impacts. Such events lead to sub-surface damages in composites which are difficult to detect during visual inspections. Also, such damages can cause significant reduction in load-carrying capacity of the structure, particularly in compression and shear. 74 impact test cases were considered to study the performance of the algorithm. Impact location and force estimated by the algorithm agreed reasonably well with measured force data from tests. Out of the 74 case of impact considered in this project around 60% of the result showed location estimation error less than 85% of results showed error less than 150mm.
In the future work, one can try to improve the results by different means, one can try other models like ARIX, ARX, State-Space model, Transfer function model etc and can do the comparisons of results to get the best approximate method. One can improve the results by generating better ARMAX models. The results can be improved using more strain sensors at appropriate locations. One can try to bond strain gauges at locations other than stringer locations also. With more strain gauges we can expect improved results. More ARMAX models can be generated at different locations. With more models we can expect to get better results.

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