Vehicle Structures Experimental Analyses

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Abstract

This paper is a summary of previous developments, publications and usage of special strain gages sets (referred to here as experimental finite elements, FEs) in experimental analyses of vehicle structures. The experimental FEs developments were based on Structural Mechanics, Math Statistic theories and experience of their applications in vehicle structures analyses and tests. The summary's objective is to describe the LS-DYNA® optional participation in experimental analyses by using experimental FEs for confirmation of analytical simulation results. Currently LS-DYNA (and its pre and post processors) have enough capability to use experimental measurement results for analytical results confirmations. However not always LS-DYNA users are familiar with the details of strain gage technology, and experimental specialists are not always familiar with the details of LS-DYNA usage of measured strains. Experimental FEs in LS-DYNA would provide a bridge between those analytical and experimental technologies. LS-DYNA users would be able to generate experimental FEs based on a vehicle structure analytical FEs model simulations results and defining structure's areas needed the simulation results experimental confirmations. That information and information specifying types of strain gages and rosettes and their locations on a vehicle structure under tests may be provided by the LS-DYNA users to experimental specialists. Based on that information the experimental specialists will conduct the structure tests and provide to the LS-DYNA users the required types and amount of strain gage measurements results.

Introduction

Traditionally vehicle body structure design comprises design analyses and physical tests. LS-DYNA® is widely used now in vehicle body structure designs by creating extremely detailed and sufficient body structure FE models simulations based on strains calculations by solving systems of equilibrium equations. In physical tests contemporary experimental analyses are based on sufficient experimental technology of strains measurements by strain gages. Both calculated and measured strains could be used in the same way in LS-DYNA simulations and experimental analyses by computing forces, stresses, velocities, est. Analytical simulation technologies are based on assumptions. Therefore experimental confirmations may be necessary. Experimental analyses results depend on types and conditions of testing as well as of the measured strains preliminary processing. The experimental confirmation level of probability depends on selected strain gages sizes, strain gage locations, magnitude of strains and type of loading: static, dynamic, impact, est. Some details of those particularities will be presented below. Some details of measurement processing with estimation of precision and acceptability for experimental FEs will be also presented. More information on experimental analyses may be found in publications (in order of publications' dates): Lasevich and others [4], [5], Shkolnikov [7]. [2], [3], [6], [1]. Detailed information related to single strain gages and rosettes may be found in Measurements Group Inc [10].

Structures Simulations and Tests Communications

All theories and analytical simulations software are based on assumptions and hypotheses which may be questionable. Sufficient communications between analytical and experimental technologies looks like as a necessary approach for the assumption and hypotheses acceptability confirmations. On Fig.1 presented is a schematic representation of a possible communication between analytical simulations and experimental analyses/tests via experimental FEs. LS-DYNA users via pre-processor could generate a structure FE model, Fig.1, and based on that model simulation results define the stricture areas requiring experimental confirmations.

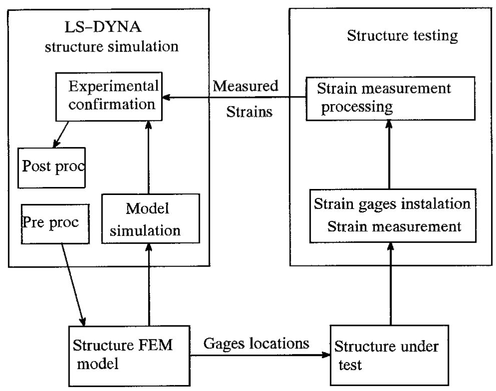

Fig.1. Schematic representation of LS-DYNA structure analytical simulation results experimental confirmation

Then a post–processor may be used to generate experimental FEs for those areas, Fig2 left. That experimental FEs can be used to define strain gages locations on the structure under tests along with types of strain gages and strain gage rosettes for installations on the structure, Fig.2 right. The defined information along with required types of the structure tests may be transferred to experimental specialists, Fig.1.

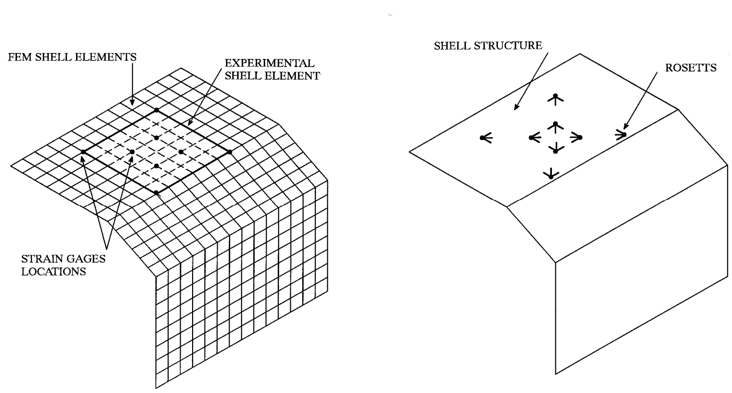

Fig.2. Left) Shell structure FE model with experimental FE defining locations of strain gages. Right) Shell structure with installed specified via experimental FEs strain gages.

The experimental specialists will install the required strain gages on the required structure under tests areas, Fig.2 right, provide structure testing, strain gage measuring, preliminary proceeding measured strains and transfer to LS-DYNA, Fig.1, the required information on the measured strains for the structure model simulation results confirmation via post-processing,

Strain Gages

Very brief strain gages information for experimental FEs is presented here. More detailed information on strain gages and rosettes may be found in Measurements Group Inc and that Company website [10].

Software for measurements structures strains via strain gages is a part of contemporary experimental technology. Therefore strain gages installation, strain measurements and initial processing of the measurements should be done during vehicle structure testing by experimental technology specialists. It is beneficial to LS-DYNA users that the strains measurements results would be preliminary processed to generate information on measurements precision and conformation that there are no strain gages with erroneous measurements. In order to have measured strains sufficient to compare with analytical results LS-DYNA users need to select and provide to experimental experts the information on locations of strain gages on the structure under tests. Also LS-DYNA users should select strain gages types and sizes based on type of tests like static, linear, nonlinear, dynamic, impact est.. Some information for the selections is in Vishay Tech Note TN-516 [11]. In Vishay Application Note TT-605 [12] there is information on strain gage usage in tests similar to crashworthiness.

Due to a possible complexity of measured strain curves (in crashworthiness tests and simulations particularly) for some measurements it may be reasonable to subdivide a measured complex digitized nonlinear strain curves into parts and replace each part by a linear $\varepsilon = \varepsilon(t)$ strain curve. The replacements by linear curve is described in very details, Shkolnikov [6], for static vehicle structure tests, and described shortly for static and dynamic tests, Shkolnikov [1], where the measured strain curve, Fig.3, is subdivided into five parts with time periods $t_i - t_{i+1}, i = 1, 2, \ldots, 5$ and replaced by linear segments. In both publications [1] and [6] statistical least squares/regression method was used.

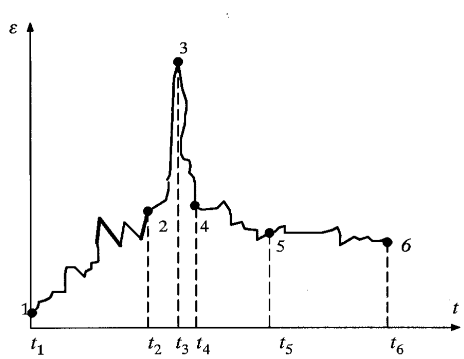

Fig.3 Measured by strain gage nonlinear strain $\varepsilon = \varepsilon(t)$ curve to be replaced by five linear regression curves, [1]

Single Strain Gage

During structure tests a single strain gage averages the strain within the gages base size, Fig.4, Shkolnikov [1], and proceeds by making the measurement curve's sharp cusp parts disappear. Therefore the measurement curve without sharp cusp parts would look like having lower strain magnitudes. If the reductions of measured strains magnitudes are significant with respect to the analytical strains curve having sharp cusp parts, the confirmation of analytical results may be considered as questionable.

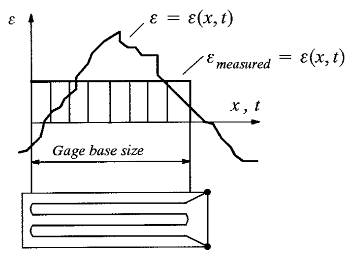

Fig.4.Measured strain curve averaging within the size of a simple strain gage base scheme shown under the curve [1]

To reduce the averaging effect may be necessary to use reduced sizes strain gages. In a strain gage scheme, Fig.4, there are several connected to each other longitudinal measuring strain wires. The wires connections are curvilinear. Strain gages measurements are also affected by deformations of those wires curvilinear connections generating transverse sensitivity specified by strain gage sensitivity factor [10]. If the structure surface under the gage has deformation not parallel to the gage's longitudinal dimension, defined by the sensitivity factor erroneous measurements may be present. To avoid errors a single strain gage should be used only in the structure areas with one dimensional deformation along the gage base. Such deformations are practically could be mostly on the structures edges. Away from a structure edges, Fig.2b, a combination of gages referred to as rosettes should be used.

Strain Gage Rosettes

There are numbers of strain gage rosettes types. Here just several types of rosettes will be presented. In general strain gage measurements may be defined as a function of three components, Eq.1 [1].

$$\varepsilon_{\varphi} = c^2\varepsilon_x + s^2\varepsilon_y + cs\gamma_{xy},\ \ c = Cos\varphi,\ s = Sin\varphi, \tag{1}$$

where ε_{φ} normal strain from a strain gage measurement; ε_x and ε_y normal strains, γ_{xy} shear strains in arbitrary xy coordinates, φ strain gage angle to coordinate x

Normal strains ε_x and ε_y, and shear strain γ_{xy} in arbitrary xy coordinates are considered as unknown strains which may be defined by solving a system of three equations, Eq.2, including measurements from three-gage rosettes, Fig.5. Rosettes having three strain gages are referred to as rosettes with required number of three strain gages, Fig.5. Such rosettes however do not provide the possibility to define three unknown strain measurement components precision.

$$\left.\begin{aligned}\varepsilon_{\varphi 1} &= c_1{}^2\varepsilon_{x1} + s_1{}^2\varepsilon_{y1} + c_1 s_1\gamma_{xy1}\\ \varepsilon_{\varphi 2} &= c_2{}^2\varepsilon_{x2} + s_2{}^2\varepsilon_{y_2} + c_2 s_2\gamma_{xy2}\\ \varepsilon_{\varphi 3} &= c_3{}^2\varepsilon_{x3} + s_3{}^2\varepsilon_{y3} + c_3 s_3\gamma_{xy3}\end{aligned}\right\}, \qquad (2)$$

where $c_i = Cos\varphi_{i,}, \; s_i = Sin\varphi_i, \; i = 1,2,3$ rosette's strain gage numbers

The Eq.2 three equations are mathematically not consistent to each other as strain measurements may have errors, which not always possible to recognize particularly as digitized nonlinear measurements are used. When measured strains are nonlinear function of time or deformations strains measurements are represented by Eq.3 and system of equations, Eq.2, should be modified. However if the digitized time or deformations steps are small $\varepsilon_x + \varepsilon_y$ is negligible with respect to number 2 and $\gamma_{xy}^2 \approx 0$, then Eq.3 may be transferred to Eq.1. In order to having small time steps during digitizing sufficiently small strain gages should be used.

$$\varepsilon_\varphi = c^2\varepsilon_x + s^2\varepsilon_y + \frac{1}{2}cs\gamma_{xy}\left(2 + \varepsilon_x + \varepsilon_y\right) + \frac{1}{8}\gamma_{xy}^2 \qquad (3)$$

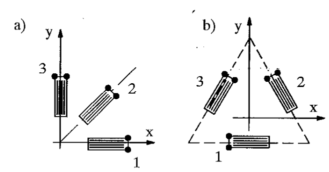

Fig.5 Rosettes with required number three strain gages

As three-gage rosettes do not provide the possibility to define strain gage measurements errors the three-gage rosettes usage is questionable and more than three gages rosettes should be used in experimental FEs for confirmation analytical results. Rosettes having more than three strain gages are referred to here as rosettes with additional number of strain gages, Fig.6. In the publications of rosettes producers like [10] and [11] mostly 2-and 3-gage rosettes are present, and sometime 4-gage rosettes are. Probably rosettes with four and more than four strain gages may be required special orders.

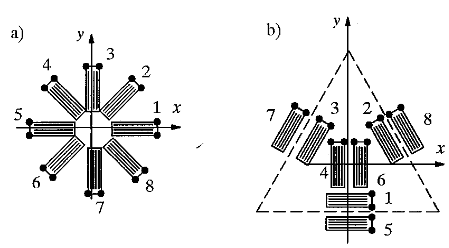

Fig.6 Rosettes with additional number of strain gages

A set of three strain gages like 1, 2, and 3, Fig.6, are required strain gages, and the combination of three gages may be different. Other than three, Fig.6, strains ages like $5, 6, \ldots, 8$ are additional strain gages. Additional strain gages allow based on measured strain ε_φ, Eq.1, estimate using least square method three strain components ε_x, ε_y, γ_{xy} (considered as unknown) and the precision of the estimation. Experience shows that when using least square estimations it is useful to make an assumption that all strain gages installed on a particular area of a structure under tests provide measurements with the same precision. That assumption may be most reasonable if in that area of the structure would be installed strain gages of the same size and types, the same measurement devices and processing would be used, est. The more strain gages installed in that area the higher least square method's precision estimation will be. If number of rosettes in that area is significant a 1-2-3-4 strain gage type rosettes, Fig.6, may be used. Up to 8 strain gages rosettes, Fig.6, may be needed if the number of rosettes is not significant.

The number of m_R systems of equations $L_j = A_j \varepsilon_j$, Eq.4, [1] represents a particular time (or displacements) step of the digitized strains curves from the number of m_R rosettes sets on plane shell experimental FEs. Each rosette has number of n_G strain gages.

$$\left.\begin{aligned} & L_j = A_j \varepsilon_j, \\ & L_j = \left[\varepsilon_1^{(j)}\ \varepsilon_2^{(j)} \ldots\ \varepsilon_{n_G}^{(j)}\right]', \\ & \varepsilon_j = \left[\varepsilon_x^{(j)}\ \varepsilon_y^{(j)}\ \gamma_{xy}^{(j)}\right]', \\ & A_j = \begin{bmatrix} c_{1,j}^2 & s_{1,j}^2 & c_{1,j}s_{1,j} \\ c_{2,j}^2 & s_{2,j}^2 & c_{2,j}s_{2,j} \\ \vdots & \vdots & \vdots \\ c_{n_G,j}^2 & s_{n_G,j}^2 & c_{n_G,j}s_{n_G,j} \end{bmatrix} \end{aligned}\right\}, \qquad (4)$$

where $i = 1, 2, \ldots, n_G$, $j = 1, 2, \cdots, m_R$, $c_{i,j} = Cos\varphi_{i,j}$, $s_{i,j} = Sin\varphi_{i,j}$, n_G is number of strain gages in each rosette, m_R is number of rosettes in a particular part of a structure under tests.

Eq.4, 5, 6, 7, 8 are used (Shkolnikov [7], [2], [3], [1], Draper & Smith [9]) to process via least square method m_R sets of digitized strains from strain gages in rosettes each having more than required number of strain gages. $\varepsilon_j = \left[\varepsilon_x^{(j)}\ \varepsilon_y^{(j)}\ \gamma_{xy}^{(j)}\right]'$, Eq.4, are vectors of unknown strains to define by the least square method. By using the least square method the estimates $\tilde{\varepsilon}_j = \left[\tilde{\varepsilon}_x^{(j)}\ \tilde{\varepsilon}_y^{(j)}\ \tilde{\gamma}_{xy}^{(j)}\right]'$, Eq.5, of vectors ε_j, Eq.4, may be defined.

$$\left.\begin{aligned} & \tilde{\varepsilon}_j = C_j^{-1} N_j,\ \ \tilde{\varepsilon}_j = \left[\tilde{\varepsilon}_x^{(j)}\ \tilde{\varepsilon}_y^{(j)}\ \tilde{\gamma}_{xy}^{(j)}\right]', \\ & N_j = A_j L_j = \left[\sum_{i=1}^{n_G} \varepsilon_{i,j} c_{i,j}^2\ \ \sum_{i=1}^{n_G} \varepsilon_{i,j} s_{i,j}^2\ \ \sum_{i=1}^{n_G} \varepsilon_{i,j} c_{i,j} s_{i,j}\right]', \\ & \tilde{L}_j = A_j \tilde{\varepsilon}_j = \left[\tilde{\varepsilon}_1^{(j)}\ \tilde{\varepsilon}_2^{(j)} \ldots\ \tilde{\varepsilon}_{n_G}^{(j)}\right]' \end{aligned}\right\}, \qquad (5)$$

where $\tilde{\varepsilon}_j$, $j = 1, 2, \ldots, m_R$ is the least square estimates of unknown vectors $\varepsilon_j = \left[\varepsilon_x^{(j)}\ \varepsilon_y^{(j)}\ \gamma_{xy}^{(j)}\right]$, $j = 1, 2, \ldots, m_R$, C_j - matrix Eq.6 [1]

$$C_j = A_j A'_j = \begin{bmatrix} \sum_{i=1}^{n_G} c_{i,j}^4 & \sum_{i=1}^{n_G} c_{i,j}^2 s_{i,j}^2 & \sum_{i=1}^{n_G} c_{i,j} s_{i,j}^3 \\ \sum_{i=1}^{n_G} c_{i,j}^2 s_{i,j}^2 & \sum_{i=1}^{n_G} s_{i,j}^4 & \sum_{i=1}^{n_G} c_{i,j}^3 s_{i,j} \\ \sum_{i=1}^{n_G} c_{i,j} s_{i,j}^3 & \sum_{i=1}^{n_G} c_{i,j}^3 s_{i,j} & \sum_{i=1}^{n_G} c_{i,j}^2 s_{i,j}^2 \end{bmatrix} \tag{6}$$

Eq. 4, 5, 6 may be used for the measured strains precisions assessments by using least square method's half of confidence intervals. Two kinds of half of confidence intervals may be used for the precisions assessments: $\Delta\tilde{L}_r^{(j)}$ and $\Delta\tilde{\varepsilon}_k^{(j)}$. The half of confidence intervals $\Delta\tilde{L}_r^{(j)}$ are for the least square estimates of $\tilde{L}_j$, $j = 1, 2, \ldots, m_R$, Eq.5, and may be defined by Eq. 7.

$$\left.\begin{array}{l} \Delta\tilde{L}_r^{(j)} = \pm\, t_{N_R}^{(P)} \left(\dfrac{\tilde{\Omega}_j \left\{A_j C_j^{-1} A'_j\right\}_{rr}}{N_R} \right)^{\frac{1}{2}}, \tilde{\Omega}_j = \sum_{r=1}^{n_G} \left[\varepsilon_{r,j} - \sum_{i=1}^{3} a_{r,i}^{(j)} \tilde{\varepsilon}_i^{(j)} \right]^2 \\ a_{r,1}^{(j)} = c_r^2,\ a_{r,2}^{(j)} = s_r^2,\ a_{r,3}^{(j)} = c_r s_r,\ r = 1, 2, \ldots, n_G \\ \tilde{\varepsilon}_1^{(j)} = \tilde{\varepsilon}_x^{(j)},\ \tilde{\varepsilon}_2^{(j)} = \tilde{\varepsilon}_y^{(j)}\ \ \tilde{\varepsilon}_3^{(j)} = \tilde{\gamma}_{xy}^{(j)},\ \ j = 1, 2, \ldots, m_R \\ N_R = \sum_{j=1}^{m_R} (n_{G,j} - n) \end{array}\right\}, \tag{7}$$

where $\tilde{\Omega}_j$ - the square of differences between measured strains $\varepsilon_{r,j}$ and estimated strains $\tilde{\varepsilon}_i^{(j)}$

The half' of confidence intervals $\Delta\varepsilon_k^{(j)}$ for the least square estimates $\tilde{\varepsilon}_j = \left[\tilde{\varepsilon}_x^{(j)}\ \tilde{\varepsilon}_y^{(j)}\ \tilde{\gamma}_{xy}^{(j)}\right]'$, Eq.5, is presented by Eq.8.

$$\left.\begin{array}{l} \Delta\tilde{\varepsilon}_k^{(j)} = \pm\, t_{N_R}^{(P)} \left(\dfrac{\tilde{\Omega}_j \left\{C_j^{-1}\right\}_{kk}}{N_R} \right)^{\frac{1}{2}}, k = 1,\ 2,\ 3, \\ \Delta\tilde{\varepsilon}_1^{(j)} = \Delta\tilde{\varepsilon}_x^{(j)},\ \Delta\tilde{\varepsilon}_2^{(j)} = \Delta\tilde{\varepsilon}_y^{(j)}\ \ \Delta\tilde{\varepsilon}_3^{(j)} = \Delta\tilde{\gamma}_{xy}^{(j)},\ \ j = 1, 2, \ldots, m_R \end{array}\right\} \tag{8}$$

In Eq.7 and Eq.8 $t_{N_R}^{(P)}$ is the Student variable for N_R number of degrees of freedom (DOF) for all m_R rosettes and confidential probability P; $n_{G,j}$ is the number of strain gages in a rosette, n is the number of unknown variables in a rosette ($n = 3$) to define.

Experimental Finite Elements

Similar to analytical experimental FEs may be of different types. Just several types of experimental FEs will be presented here to illustrate some FEs particularities. More detailed information is in previous publications Shkolnikov [1], [2], [3].

Experimental Shell FEs

In Fig.7, Shkolnikov [2], [1], presented are two types of experimental shell FEs over several analytical shell FEs (dotted lines). Eq. $1, 2, \ldots 8$ are for experimental shell FEs. On the Fig.7 left side very thin thickness analytical shell FEs are considered as having strains $\varepsilon_x, \varepsilon_y, \gamma_{xy}$ only in xy plane. Therefore the experimental shell FE is considered having 12 DOF, and 12 is a required number of strain gages in 4 rosettes to be included on that experimental shell FE. Those 4 rosettes would not provide the possibility to assess the precision of strain measurements. Additional strain gages providing the possibility assessing the precision of strain measurements should be on the rosettes based on the considerations described above.

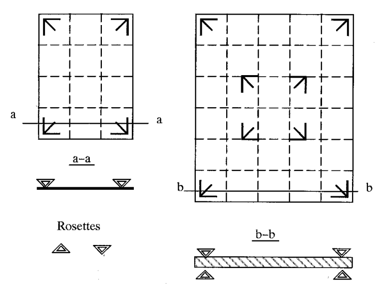

Fig.7. Experimental shell FEs over analytical shell FEs (dotted lines)

The in xy plane strains assumption is not always sufficient for the real thin walled shell structures. Shells may have local bending deformations due to local shell unevenness. Therefore the Fig.7 left side experimental shell FE may require having rosettes on both side xy surfaces. On the Fig.7 right side is a set of thick analytical shell elements considered having on both side surfaces strains in xy coordinates from in plane and bending deformations. Therefore the experimental shell FE over those analytical elements should have 8 rosettes (each having required three strain gages) on each surface and having 48 DOF. Additional strain gages for those rosettes are required. Also may be on that structure area instead of one, as shown on Fig.7, 4 experimental shells FEs having rosettes with more than 3 strain gages should be. The final decision must be based on analytical simulation results and taking into the types of external loads (static, impact, est.), est. on the structure.

Experimental Cylindrical Shell/Beam FEs

Detailed description of cylindrical shell analytical FEs is in Shkolnikov [8]. Detailed description of cylindrical shell/beam experimental FEs is in Shkolnikov [3], [1], where there are equations similar by requirements to Eq.1, Eq.3, Eq.4,$\because$,Eq.8, but having $n = 4$ instead of $n = 3$ and developed for cylindrical shell/beam experimental FEs

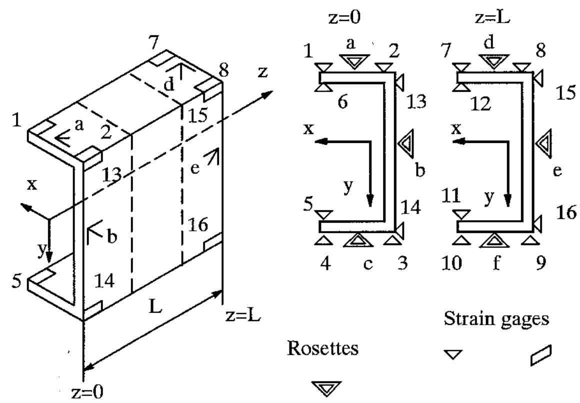

Fig.8. Cylindrical shell or thin walled open cross section beam experimental FE over cylindrical shell/beam analytical FEs (dotted lines)

On Fig.8 [1], presented cylindrical shell/beam experimental FE having singular strain gages where one dimensional deformations are considered to be, and having rosettes where mostly shear strains are expected. Again the final decision on strain gage options must be based on analytical simulation results, types of external loads (static, impact, est.), est. If the cylindrical shell cross section is confirmed to be non deformable, the required number of strain gages on each side of experimental FE is $n = 4$ plus 3 thee-gage rosettes. All other strain gages will be considered as additional. When nonlinear deformations are started and the cylindrical shell/beam cross sections started to be deformable analytical cylindrical shell/beam FEs may be necessary to replace with analytical plane shell elements. If such possibility is predictable may be on experimental FEs some singular strain gages, Fig.8, should be replaced by rosettes with more additional strain ages.

Conclusions

1. Contemporary vehicle structures analytical FEs simulations sometime require experimental confirmations by using as an option experimental FEs.
2. Experimental FEs provide a bridge between analytical and experimental analyses. That could provide better capabilities for confirmation FE simulations results by experimental analyses results.
3. Experimental FEs could be developed via LS-DYNA pre processor based on vehicle body structure FE model simulation results defining structure's areas requiring experimental conformations.
4. By using experimental FEs LS-DYNA users could provide to experimental specialists the information on strain gages and rosettes types and their locations on a structure under tests, and specify the experimental results needed for FE simulation results confirmation.
5. Experimental specialists based on the information from LS-DYNA users could install on a structure under tests strain gages and rosettes, conduct the structure tests and provide to the users the necessary experimental strain gage preliminary processed strain measurements results.

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