1. Introduction

The use of steel plate shear wall (SPSW) as a primary lateral load resisting system in the construction of new buildings and for upgrading the lateral load resistance of an existing structure, began in the early 1980s in USA and Japan. In its typical form, the SPSW system consists of a steel plate shear panel added as an infill to the building structural frame composed of beams (horizontal boundary elements) and columns (vertical boundary elements). Using the thick or stiffened SPSW is an unattractive option because of its higher cost in comparison to reinforced concrete shear walls. This has led to a gradual and general shift towards the use of thin un-stiffened SPSW. In this arrangement, the steel plate is expected to buckle along compressive diagonal under relatively small shear forces. After buckling, the storey shear force is resisted by the steel plate through the formation of a tension field as explained in pictorial form in figure 1.

Expanded metal mesh (EMM), figure 2b, is a sheet of metal, slit and stretched into a non-raveling unit of uniform-sized, diamond-shaped openings as shown in figure 2a. No metal is lost in the expanding process and the final product is stronger per kilogram and lighter per meter than the original sheet. Expanded metal mesh has no welds, seams or jointed areas. It is more durable and maintenance-free
than other similar materials. At present, some experts have done research on the expanded metal mesh. The main research areas are as follows:

Investigation on a) natural period of vibration [3] b) its seismic application [4] c) behavior of EMM under shear loading [5, 6] d) use of EMM for retrofitting of RCC moment resisting frames [7] and e) Investigation of energy absorption characteristics of EMM [8]. A study of available codes on expanded metal mesh [9-12] reveals that these codes only specify workmanship, quality control, etc. but do not give information about the strength of expanded metal mesh as a whole or in terms of the strength of its components. Thus, the designer has no idea about the properties of EMM as a whole or in terms of its component. Therefore, it is necessary to perform extensive tests to understand the behavior of EMM as a whole and to propose a correlation between the strength of the parent material (material from which EMM is manufactured) and that of the finished product (EMM). To achieve this objective, the work of statistical characterization of EMM strand has been undertaken. Relevant papers on statistical characterization have been studied for fixing the methodology of statistical characterization of EMM strand [13].

Figure 1. Explanatory sketch of diagonal tension field theory [1].

Figure 2. a) Process of making expanded metal mesh [2] b) sketch of expanded metal mesh.

2. Statistical characterisation of expanded metal mesh strand

None of the codes [9-12] specify values of tensile, bending and shear strength of the EMM strand or EMM panel as a whole. Hence, to predict the behavior of EMM from the properties of the parent metal, it is necessary to carry out extensive testing and to establish the statistical characterization of EMM strand. Three sizes of EMM 115x40x4x4mm, 115x40x5x5mm and 115x40x5x6mm were manufactured from a sheet of steel complying with the requirements of IS 2062:2011(specification for hot rolled medium and high tensile structural steel). The present paper consists of two parts viz. laboratory experiments and statistical analyses. The laboratory experiments include a) Coupon tests of the original sheet metal (30 or more number of tests) b) Tension tests on individual strands of EMM (30 or more number of tests) for each of the three sizes (cross-section) of the strand (4x4mm, 5x5mm, and 5x6mm). The statistical analyses focus on recommending nominal/design values for basic mechanical properties of sheet metal and EMM, based on sound statistical methods, applied to the experimental observations. For statistical characterization, the minimum number of tests required to be done is decided.
as per the recommendation of paper [13] and accordingly, at least 30 numbers of specimens for each size of strand were tested. The stress-strain curve for a coupon of parent material and a strand of the finished product (EMM) is presented in figures 3 and 4 respectively. A photograph of tests being conducted is shown in figure 5a and 5b respectively.

It is a fact that for mild steel parent material, the slitting and stretching process adopted in the manufacturing of EMM leads to strain hardening. Due to this strain hardening, the stress-strain graph of the strand does not indicate a well defined yield point. Therefore, to obtain the yield stress, 0.2% proof stress for the strand is adopted, as per IS 1608:2005. As shown in figure 4, a tangent line with the initial slope of the stress-strain graph is drawn. The point of intersection of this line with the x-axis is obtained. Next, another line is drawn at an offset of 0.2% from this line. The yield point is the y-coordinate of the point of intersection of 0.2% offset line and stress vs. strain (% elongation) curve.

For experimental data generally 80 to 100% confidence level ‘γ’ is assumed and 5 percentile ‘p’ i.e 95% probability of success is assumed similar to the practice adopted by IS code, for finding the characteristic strength of the material. The same has been employed in this study. As per [14] an order of examining probability distributions is to examine first the two-parameter Weibull CDF; if this distribution is not rejected by a statistical hypothesis test, it is chosen and no further distribution is examined. If the Weibull CDF is rejected, then other distributions (lognormal and normal) are examined in a prescribed order. The stepwise procedure adopted is described in the following.

1) The values of thickness, width, yield stress, ultimate stress and maximum % elongation for the set of 30 specimens, for sheet metal and each size of strand were obtained from tension tests on these specimens.

2) The normal, lognormal and Weibull distribution (CDF, PDF) curves were plotted for the above data.
3) Anderson Darling statistic, which is sensitive to discrepancies in the tail region, was found using the equation mentioned in table 1

### Table 1. Probability density function

| Property | Normal | Lognormal | Weibull |
|----------|--------|-----------|---------|
| Variable | \(-\infty < x < \infty\) | \(0 \leq x < \infty\) | \(0 \leq x < \infty\) |
| Probability density function \(f_x(x)\) | \(\frac{1}{\sigma \sqrt{2 \pi}} \exp \left[ -\frac{1}{2} \left( \frac{x - \mu}{\sigma} \right)^2 \right]\) | \(\frac{1}{x \sqrt{2 \pi}} \exp \left[ -\frac{1}{2} \left( \ln x - \lambda \right)^2 \right]\) | \((\frac{\beta}{\alpha}) x^{-\frac{\beta-1}{\alpha}} \exp \left[ -\left( \frac{x}{\xi} \right)^\beta \right]\) |

AD Anderson-Darling
\[
A_n^2 = \frac{1}{n} \sum_{i=1}^{n} \left[ \frac{1}{2} \ln \left( F_0(x_i) \right) \right] - n
\] (1)

\[
\sum_{i=1}^{n} x_i^\beta \ln(x_i) \sum_{i=1}^{n} x_i^\beta = \frac{1}{\beta} - \frac{1}{n} \sum_{i=1}^{n} \ln(x_i) = 0
\] (2)

\[
\hat{\alpha} = \left( \frac{n \sum_{i=1}^{n} x_i^\beta}{\sum_{i=1}^{n} x_i^\beta} \right)^{\frac{1}{\beta}}
\] (3)

5) If OSL < 0.05, then that particular distribution was rejected (this is statistical hypothesis test)

6) Maximum likelihood estimator (MLE) of parameter \(\alpha\) (scale parameter) and \(\beta\) (Shape parameter) are \(\hat{\alpha}\) and \(\hat{\beta}\) defined by expression (2) and (3) respectively.

7) Using values of \(\hat{\alpha}\) and \(\hat{\beta}\) obtained from Eq. (2) and (3), the mean and cov were evaluated.

\[
\text{mean} = \hat{\alpha} \Gamma \left( 1 + \frac{1}{\beta} \right)
\] (4)

\[
\text{cov} = \frac{\Gamma \left( 1 + \frac{2}{\beta} \right) - \Gamma^2 \left( 1 + \frac{1}{\beta} \right)}{\Gamma \left( 1 + \frac{1}{\beta} \right)}
\] (5)

Where ‘\(\Gamma\)’ is the gamma function.

8) Next, MLE of the 5th percentile value \(X_{0.05}\) is obtained from equation (7).

\[
x_p = \hat{\alpha} \left[ -\ln(1 - p) \right]^{\frac{1}{\beta}}
\] (6)

\[
x_{0.05} = \hat{\alpha} \left[ 0.0513 \right]^{\frac{1}{\beta}}
\] (7)

9) The data confidence factor \(\Omega\) (function of cov of the data and sample size \(n\)) is then obtained from table no. 2 given in [13].

\[
\Omega = e^{-\frac{U_{1-\gamma}}{\sqrt{n} \beta}}
\] (8)

10) The nominal value for which there is 80% confidence that 95% of the population is above this value can be evaluated from equation (10).

\[
x_{p,\gamma} = \Omega x_p
\]

\[
x_{0.05,0.80} = \Omega x_{0.05}
\] (9) (10)
3. Results
From the repetitive tensile test carried out on coupon specimen and on each size of EMM strand, values of proof stress/yield stress, ultimate stress and maximum % elongation are obtained. This data set of each property is checked for the best distribution it fits and following the statistical characterisation procedure, given in section 2, nominal/design values of each material property are obtained. Sample histogram of proof stress, ultimate stress and % elongation for coupon tests and

![Histograms](image1)

**Figure 6.** Histogram of a) yield stress of coupon and b) ultimate stress of coupon

**Figure 7.** Histogram of a) proof stress of 6 mm strand and b) ultimate stress of 6 mm Strand

![Histograms](image2)

**Figure 8.** Histogram of a) maximum % elongation of 6 mm strand and b) maximum % elongation of coupon

![Histograms](image3)

**Figure 9.** PDF of Weibull distribution for proof stress of 6 mm strand specimen

**Figure 10.** Representative, CDF Weibull distribution for proof stress of 5x6 mm strand specimen

![Histograms](image4)

**Figure 11.** Comparison of the statistical characteristic nominal yield stress of strand with parent material

![Histograms](image5)

**Figure 12.** Comparison of statistical characteristic ultimate stress of strand with parent material
strand tests is presented in figures 6, 7 and 8 respectively. All the specimens fit into the Weibull distribution. Details of the statistical parameters of each of the Weibull distributions are given in table 2 and 3 respectively. Comparison of statistical characteristic nominal yield stress, ultimate stress and % elongation of the strand with the coupon is presented in figure 11, 12 and 13 respectively. Representative, PDF, and CDF for Weibull distribution of 5x6mm strand is shown in figure 9 and 10 respectively.

3.1 Observations and discussion

It is observed that all the strands had broken close to the knuckle. This is understood from the strain values obtained from tension test on 4 numbers of strands with 4 numbers of strain gauges, two each at the center and near the join (knuckle), refer figure 5c. Because the adjacent strands are eccentric (eccentricity \( e = \) width of the strand), the joint is subjected to axial force and bending moment \( (F_e) \) due to this eccentric force. So there is the highest strain at the inner side of each joint and lowest on the opposite side (almost compressive), this indicates that failure is due to combined axial and bending effect.

The strand was manufactured from IS 2062:2011 grade of steel. For coupons, the statistical characteristic yield stress and statistical characteristic ultimate stress obtained were 238.02 N/mm² and 316.2 N/mm² respectively. For strands, the statistical characteristic 0.2% proof stress for 4x4, 5x5 and 5x6 mm size of strands obtained were 237.02, 235.7 and 230.24 N/mm² respectively. The statistical characteristic ultimate strengths obtained for 4x4, 5x5 and 5x6 mm size of strands were 313.78, 289.16 and 292.62 N/mm² respectively. The 0.2% proof stress and the ultimate strength of strands are less than the corresponding coupon stresses. This may be due to the combined effect of axial and bending forces at the joint.

It is also observed that the stresses decrease with an increase in the strand width. This may be due to an increase in the moment at the knuckle because an increase in the width leads to higher eccentricity between the line of action of forces \( (i.e.e) \). To verify this, a tension test of the strand was simulated in ABAQUS 6.13[15] and parametric studies were done for strands of increasing widths. It was found that the stresses decrease with the increase in the strand width.

Though the strand is manufactured from mild steel, its stress-strain graph did not show a well-defined yield point. The coupon tests on parent material have shown average maximum elongation of 31.55% while the tests on 4x4, 5x5 and 5x6 mm strands have shown maximum elongations of 5.4%, 9.72%, and 9.29% respectively. This may be due to cold form process of manufacturing EMM.
Table 2. Summary of Weibull distribution for
(a) yield/proof stress of 4,5,6mm strand and 4mm coupon specimen (N/mm²)
(b) ultimate stress of 4,5,6mm strand and 4mm coupon specimen (N/mm²)

|                | 4x4mm strand | 5x5mm strand | 5x6mm strand | Coupon | 4x4mm strand | 5x5mm strand | 5x6mm strand | Coupon |
|----------------|--------------|--------------|--------------|--------|--------------|--------------|--------------|--------|
| Number of data points | 31           | 35           | 35           | 38     | 31           | 35           | 35           | 38     |
| Sample mean      | 249.039      | 259.321      | 242.954      | 261.946| 352.34       | 318.26       | 340.33       |        |
| Sample Sigma     | 5.298        | 11.667       | 5.967        | 10.655 | 18.572       | 14.955       | 13.305       | 10.41 |
| cov              | 0.021        | 0.045        | 0.025        | 0.041  | 0.053        | 0.047        | 0.041        | 0.03  |
| AD test statistic| 0.557        | 0.574        | 0.647        | 0.717  | 0.709        | 0.251        | 0.615        | 2.00  |
| AD* test statistic| 0.577       | 0.594        | 0.669        | 0.740  | 0.734        | 0.259        | 0.636        | 2.07  |
| OSL              | 0.137        | 0.129        | 0.083        | 0.053  | 0.054        | 0.444        | 0.097        | 0.36  |
| Nominal value    | 237.017      | 235.699      | 230.240      | 238.015| 13.775       | 289.161      | 292.622      | 316.204|

Table 3. Summary of Weibull distribution for % elongation of 4,5,6mm strand and coupon specimen (N/mm²)

|                | 4x4mm strand | 5x5mm strand | 5x6mm strand | Coupon |
|----------------|--------------|--------------|--------------|--------|
| Number of data points | 31           | 35           | 35           | 35     |
| Sample Mean      | 5.460        | 9.720        | 9.285        | 37.063 |
| Sample Sigma     | 2.417        | 2.992        | 3.291        | 2.791  |
| COV              | 0.443        | 0.308        | 0.354        | 0.075  |
| AD test statistic| 0.658        | 0.632        | 0.720        | 0.590  |
| AD* test statistic| 0.682       | 0.654        | 0.745        | 0.609  |
| OSL              | 0.078        | 0.091        | 0.054        | 0.118  |
| Nominal value    | 1.854        | 4.892        | 4.114        | 31.555 |

Table 4. Correlation, statistical characteristic nominal design value of strand in % as compare to coupon values

|                | Coupon test | 4x4mm strand | 5x5mm strand | 5x6mm strand |
|----------------|-------------|--------------|--------------|--------------|
|                | N/mm²       | %            | %            | %            |
| Yield stress   | 238.015     | -0.42        | -0.97        | -3.27        |
| Ultimate stress| 316.204     | -0.77        | -8.55        | -7.46        |
| Maximum% elongation | 31.555   | -94.12       | -84.50       | -86.96       |

4. Conclusions
The yield stress, ultimate stress and % elongation of finished product i.e strand of EMM, is less than that of the parent material. This is mainly due to the combined axial and bending effect at the knuckle, cold form process of manufacturing EMM and irregular geometry of EMM. From table 4 it is evident that the stress of strand also decreases with an increase in its width. This is due to higher eccentricity.
with an increase in width, which results in inflation of bending effect near the knuckle. Thus, more the eccentricity lesser will be stress.

On the basis of statistical characterisation done in this study and comparative values recorded in table 4, it can be concluded that after applying an appropriate reduction factor to properties of parent material, sufficiently accurate nominal design stress values of the finished product can be estimated. This estimated value can be used by the designer to either predict the behaviour of EMM as a whole or to design the structure with EMM as lateral load resisting system, for low seismicity situations. In continuation of this study, further experimentation on the whole EMM is carried out. As per this study, a reduction factor of 0.95 for yield stress and 0.90 for ultimate stress is proposed to be used for predicting the nominal design values of EMM strand (up to strand width of 6 mm) from respective stress of parent material.

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