Numerical investigation of the performance of Long-span Pocket-type Rock-net at various loading parameters resulting into the same specified impact-energy

Rockfall protection, Impact- energy,
Long-span Pocket-type Rock-net,
Loading parameters, Finite element analysis

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1. Introduction

In Japan, after a dozen of full-scale tests (FSTs) over a couple of past decades, an award-winning new design of rockfall protection cable-net structure called Long-span Pocket-type Rock-net (LPR) has been introduced into practice. The steel structure of LPR essentially consists of a net-mesh reinforced with horizontal- and vertical-cables (wire-ropes) and supported by a sag-cable which runs through the slanted posts at two ends spaced at a certain horizontal distance called span. All the horizontal-cables, sag-cable and post-supporting guy-cables are ground to anchors with an appropriate arrangement of friction-brake elements (U-bolt Type Damper: UTD) connected at their ends.

While verifying the performance of the proposed LPR structures by FSTs, the net was hit at a point (mid-span, 3/4th height from the bottom) [1] with a mass of certain velocity resulting into the specified impact-energy (half the product of mass and velocity squared). For example, a case of LPR taken as a reference case in this research (RC-LPR) of the so called design impact-energy of 150 kJ (Fig. 1) was tested with a cylindrical concrete-block of 1t mass hitting the net horizontally with a velocity of 17.33 m/s. However, it is quite practical that there can be a number of combinations of velocity and mass resulting into a given kinetic energy. Moreover, if given the velocity be fixed, the mass itself has density and volume as its ingredients. Again, if the density is fixed at some logical practical value, size (volume) will have a unique value, but again there may come shape as another variable. It may be very difficult or even impossible to predict or simulate the exact shape of the falling rock-block; however, effect of the idealization of the shape in the performance of the LPR should be evaluated. Moreover, the impact-point and multi-body impact are likely to be other important sets of loading parameters to be considered.

In fact, European guideline [2] for testing “rockfall net fences” requires hitting the net at the center (both for “SEL” and “MEL” design checks) by a polygonal (octagonal) block of certain specified geometry. There is a limit for rock-density as 2500-3000 kg/m^3 and impact velocity to be 25 m/s or greater. Nevertheless, the European literatures available so far, which includes the special program FARO [3], use sphere to simulate rock-block. There are certainly a very few relevant literatures [4, 5] which have identified or dealt with the effect of mass or shape of the impacting object on the displacement-performance of the target object, but they are either preliminary or very limited.

Thus, it appears that specifying a single value of impact-energy for the design of a LPR may not be sufficient. The scientific evaluation of the effects of the various loading parameters resulting into the same specified impact-energy in relation to the proposed ultimate goal to devise design charts / guideline for LPR structures should be an original research problem statement. Under this hypothesis, the authors have been making investigations to answer the various above raised questions by numerical approach using the reliable program LS-DYNA as the major tool, and this paper reports the summary of the some progress on it.

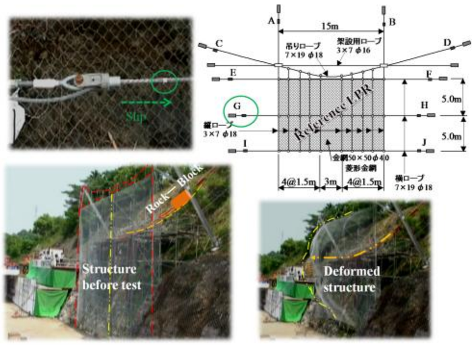

Fig. 1: RC-LPR & its FST Scenario: Max. out-of-plane displacement of net = 3.5 m; Maximum tension, at H = 94 kN; Maximum slip of UTD, at H = 134 mm.

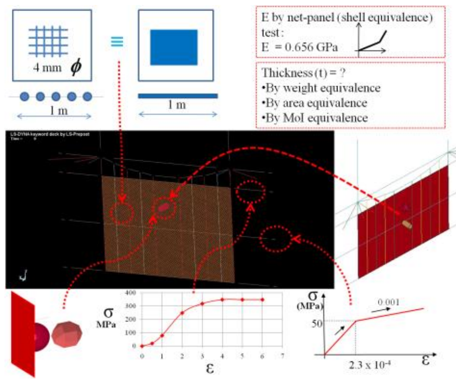

Fig. 2: FE model of RC-LPR with major important aspects of modeling and loading parameters; viz. equivalent shell modeling; constitutive modeling of UTD; idealized rock-blocks, impact points; etc.

Table 1: Max. out-of-plane displacement response (Dm) of RC-LPR at various loading parameters with constant impact-energy = 150 kJ

(a) D_m (m) for E = 150 kJ, V =17.33 m/s; L/ø Ratio = 2; *

Rock Density (kg/m^3)	Cyldr. Dia. (m)	D_m
2600	0.625	3.60
5000	0.500	3.48

(b) D_m (m) for E = 150 kJ, ρ= 2600 kg/m^3; L/ø Ratio = 2; *

Velocity (m/s)	Cylinder Dia. (m)	D_m
17.33	0.625	3.60
25.00	0.500	3.10

(c) D_m (m) for E = 150 kJ, V =17.33 m/s; ρ= 2600 kg/m^3 ;*

L/ø Ratio (ø)	D_m
1 (0.788 m)	3.55
2 (0.625 m)	3.60
3 (0.546 m)	3.40

(d) D_m (m) for E = 150 kJ, V =17.33 m/s; ρ=2600 kg/m^3; Cyldr. L/ø Ratio = 2

Impact Point	Cylinder D_m	Sphere D_m	Octagon D_m
*3/4th Height	3.60	3.38	3.48
Middle Height	3.74	3.45	3.57

2. Methodology

As stated earlier, RC-LPR [Fig.1] was taken as the reference case for investigation. It was then modeled numerically using appropriate finite elements and material models inbuilt in JVISION (preprocessor), [Fig.2]. The net was modeled with Belytschko-Tsay Shell element at 50 mm x 50 mm discretization. The cables were modeled with 2-node Discrete Beam (Cable) elements while the posts were modeled with Beam (Truss) element. The adopted material models for net, cables and posts were respectively, Fabric (Mat034), Cable Discrete Beam (Mat071) and Plastic Kinematic (Mat003).

As per their calibration, for cables, the nonlinear stress-strain curve obtained from the laboratory test was assigned; while for net and post, the specified constitutive parameters were assigned in the inbuilt models. Regarding modeling of the UTD, we assumed it be modeled by a Truss element of appropriate constitutive law such that its axial elongation may equivalently represent the slippage. Based on the physical observation as well as the performance observed in FSTs (break load of UTD is 50 kN, but the tension in the corresponding cable in FST is much higher), we assumed that the plastic kinematic hardening model may represent the behavior of the UTD. The model was then calibrated from the available FST result. Finally the keyword input file prepared from JVISION was then analyzed in LS-DYNA.

Indeed, numerically simulating the out-of-plane deformation of net is also a challenge. But, we have addressed this macroscopically in a simplified way by modeling the net by the finite element shell-mesh with its constitutive parameters determined from the net-panel center-point load test. To simulate the stiffness influenced by the section geometry, parametric back analyses were carried out, which suggested that the FST results could be simulated when the shell thickness of 100 mm (calculated from the weight-equivalence of the real net used in FST) was halved. With the modified model, analyses were carried out for various loading parameters as discussed in the introduction keeping the impact-energy to be constant. After identifying that the velocity and the density do affect the performance of LPR to facilitate performance-comparison for remaining parameters, we fixed the density to 2600 kg/m^3 and velocity to 17.33 m/s complying with the FST situation. Here, we have given emphasis to the performance- comparison for only three rock-block shapes (cylinder, sphere and octagon) and two impact-points (3/4th height and mid-height, each at mid-span) as they are found most commonly pronounced in available literatures. Amongst the various responses of interest, the out-of-the plane net displacement (D_m) has been presented as the most important response [5] for comparison.

3. Results and discussion

Fig. 3 (a)-(c) represents some selected numerical simulation results (structural performance of LPR) verified through the corresponding FST results. As depicted from Fig. 3 (d), the UTD's role has not been very significant; it is contributing only to some 15% of the total impact-energy. A separate detail analysis on the constitutive modeling and optimization of UTD may be found in a separate publication of the authors.

Table 1(a)-(d) show the D_m-response of RC-LPR at various loading parameters. The data clearly demonstrate the effects of the ingredient parameters of the specified impact-energy. Looking at the displacement responses presented in Table 1(d), when compared row-wise, the displacement response of RC-LPR is highest for the cylindrical block, while it is lowest for sphere. For a given impact energy of 150 kJ, the differences accounts up to 30 cm. The response for the octagonal block impact has been obtained interestingly to be an average of the extremes. Now, if we compare the results in the same table column-wise, we can see that the displacement response is higher for the central impact. The difference here is, however, smaller, with maximum in the case of cylindrical block.

The force responses (not shown) are however, higher for lower displacement responses. Therefore, it seems that the choice of cylinder for the test of RC-LPR was rational from the point of view of displacement response, but at the same time it underestimated the tension forces in cables.

In multi-block impact, for the sake of analysis, the above two extreme conditions were simulated together (with 300 kJ) and compared with single block-impact energy of same energy, which resulted into different response-displacement values; respectively 4.24 m and 4.51 m.

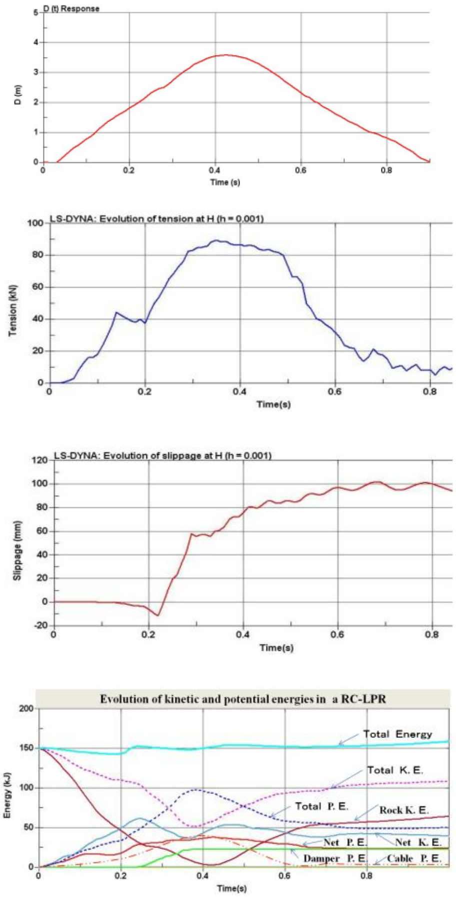

Fig. 3: Numerical simulation of RC-LPR: Max. out-of-plane displacement = 3.6 m; Max. tension in cable, at H = 90 kN; Maximum slip of UTD, at H = 100 mm.

To interpret the results analytically, the models presented in Fig. 4 (a)-(c) are assumed to work well. Effect of the impact point related parameters shall be interpreted with the model of a bending member resting over spring supports, and the SDOF mass-spring dynamic model shall be employed to interpret the effects of the rock-block shape and size related parameters. The results for the multi-block impact may be simply interpreted from the comparison of a bending member subjected to a point load, against two point loads of total magnitude equal to the single point load.

4. Conclusions

- Specifying only the impact energy to classify LPR (and probably other rock-net structures too) may be misleading because our investigation reveals that the structural performance of LPR is different at different loading features resulting into the same specified impact energy.
- While effort is being made to prepare the design guidelines (handbook) of LPRs, it is advised to derive the design charts wherein there exist the response curves (such as displacement versus energy) with impact-velocity as well as the idealized rock- block size also as the variables to be specified. Then the user of the chart (designer) shall choose his appropriate curve.
- Similarly, it is suggested to incorporate the effects of idealized shape of rock-block, and the specified point of impact either explicitly or implicitly. For example, our preliminary analysis results reveal that, implicitly, the design (or design charts) of LPR shall be such that the net-displacement based responses be evaluated from the simulation of impact by the spherical rock-block, hitting at the 3/4th height, whilst the force (cable-tension)-based performance be evaluated from that by a cylindrical rock-block hitting at the center.

Efforts for the analytical interpretation of the results still continue.

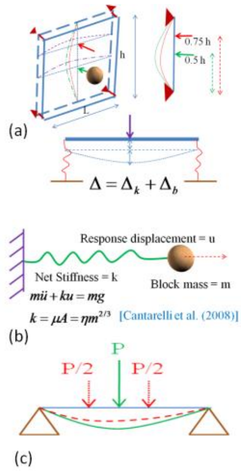

Fig. 4: Analytical models proposed for the interpretation/validation of results

Acknowledgements:
Thankful to Daiichi Consultants Co. /Kochi, and Nihon Protect Co. /Matsuyama for providing useful test results related to LPR.

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