CDOT Flexpost Rockfall Fence Development, Testing, and Analysis

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Highways in Colorado are being protected against rockfall hazard by a new flexible fence developed in a 2-year program of prototype testing and dynamic analysis. The Flexpost rockfall fence consists of steel gabion mesh and wire rope supported on flexible posts constructed of steel pipe and 7-wire strands that are capable of elastic rotations in excess of 90 degrees out of the vertical. The rotation capacity of the posts allows the fence to respond to rockfall impact with large elastic deformation and to rebound after impact. The fence does not employ out-of-place stays, which would hamper the use of equipment to clear rockfall debris. In impacts by massive, high-velocity rocks, tensions in the steel fabric impose a centripetal acceleration on the rock and lead it to an impact with the ground, dissipating the rockfall kinetic energy. Flexpost fence prototypes were tested with rocks falling freely down a natural slope. The tests provided basic data on rockfall capacity, which were further refined by dynamic analysis using software developed specifically for the Flexpost fence. The dynamic analysis treats the fence and falling rock as separate bodies, computes contact forces, and includes modeling of a moving contact area. Analysis of prototype test cases agreed with the field observations. Flexpost fences are made of lightweight, readily available components, are inexpensive, and are already in service in Colorado.

To minimize rockfall hazard along its roads, the Colorado Department of Transportation (CDOT) maintains an active program of research into rockfall hazard prediction and mitigation. This effort has produced techniques for computer simulation of rockfall events and computation of site-specific statistics of rockfall hazard, and has led to the design and testing of innovative rockfall barriers, including earth-filled timber cribs, geofabric walls, kinetic energy attenuators, and the Flexpost rockfall fence (1,2).

Rockfall barriers are intended to prevent rocks in motion from reaching roadways and are designed for impact. The input is the kinetic energy of a falling rock, and the barrier must dissipate this energy. Impact force depends on rockfall kinetic energy and on the stiffness and mass of the barrier. Within limits, it is possible to manipulate impact force through structural design. The trade is one of greater deflection for lower force. Rigid barriers respond to rockfall impact with high force. Flexible, compliant barriers respond to the same impacts with lower force.

The Flexpost rockfall fence is compliant. The fence is a fabric of steel mesh and wire rope supported on spring-mounted posts (see Figure 1). The posts can rotate elastically through angles more than 90 degrees out of the vertical and develop

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only a modest resisting moment. The capacity for elastic rotation in the posts provides a large capacity for elastic deflection of the fence. Because of the low-force, elastic behavior of the posts, impact forces are reduced and the fence rebounds to be ready for other rockfalls. The fence fabric is initially slack and easily forms a pocket to trap incident rocks. In impacts by large, fast-moving rocks it is observed that the fence imposes a centripetal acceleration on the rock, leading it to an impact with the ground, which is used as a massive barrier to absorb rockfall energy. Other rockfall fence designs are comparatively rigid and may allow large permanent deflections by the use of uphill cable stays and slip mechanisms. Such fences cannot rebound, and the stays interfere with equipment for clearing. The Flexpost design avoids both of these limitations.

FLEXPOST ROCKFALL FENCE DESIGN

The Flexpost fence is constructed of steel gabion mesh and interwoven wire ropes supported on flexible posts. The fence is 11 ft tall with posts spaced 16 ft for interior panels and at 8 ft for end panels. The gabion mesh is suspended from a top cable along the length of the structure and wrapped around end posts. The top cable is clamped to the top of each post. Three intermediate cables are woven into the mesh as reinforcement and are attached to end posts. A bottom cable is woven into the mesh, anchored to foundations at the end posts, and connected to intermediate post foundations by 3-ft cable tethers. Cable stays run from each post foundation to the tops of adjoining posts and form X-bracing in each panel. The cable stays carry tensile loads to the post foundations during rockfall impact and constrain the posts to rotate normal to the fence run.

Each post is made of two lengths of 3-in. inside diameter steel pipe encasing a group of 7-wire prestressing strands. One length of pipe serves as a ground casing. Posts are founded by grouting this casing into the earth. The upper length is the visible post. A group of 19 prestressing strands are grouted into both pipe lengths. At the ground surface between the two pipe lengths, 18 in. of the strand group is left without casing. The unencased strands bend easily, allowing each post to behave like a bar on a spring-loaded pivot. The strands allow elastic rotations of posts in excess of 90 degrees and posts can be bent over to touch the ground and will spring back when released. In Figure 1, the total strand length is indicated in the post on the left.

Flexpost rotational stiffness was determined in 16 static tests of six posts. Flexposts were loaded at the top by a cable attached to a hydraulic ram. Cable tension was calculated from hydraulic pressure readings and ram calibration. Hori-
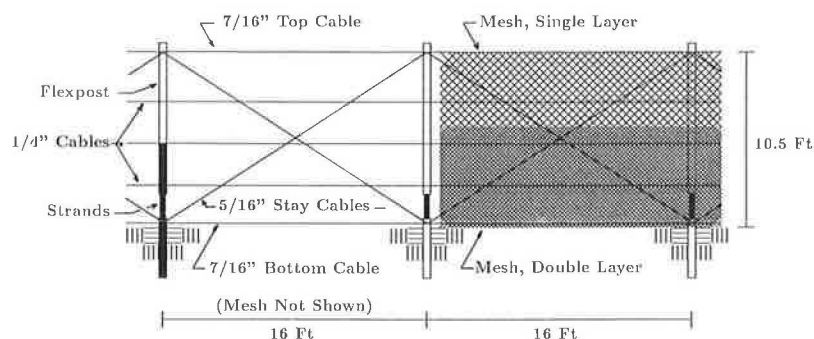
FIGURE 1   CDOT Flexpost rockfall fence elevation.

zontal and vertical deflections of the tops of the posts were recorded along with ram hydraulic pressure readings, and the data were used to compute base moment M and post rotation θ. Flexposts exhibit bilinear M versus θ behavior with an initial tangent stiffness of 90,000 ft-lb/rad for moments up to 2,300 ft-lb, and a second tangent stiffness of 1,600 ft-lb/rad for higher moments. The average M versus θ curve obtained from static tests is shown in Figure 2.
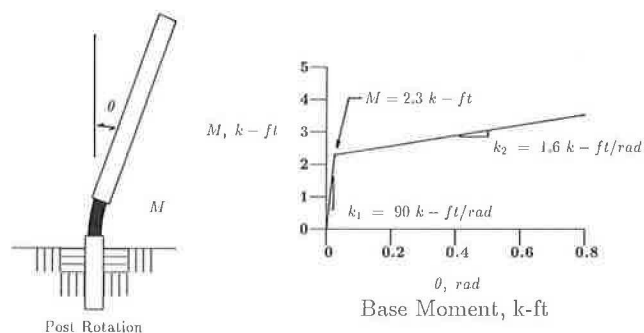

FIGURE 2   Flexpost static tests.

PROTOTYPES AND ROCKFALL TESTS

The first prototype Flexpost fence was built in 1989, and two additional prototypes, both incorporating design advances, were built and tested in 1990. Schematics of the prototypes are shown in Figure 3. The 1989 fence was 6 ft tall and had six posts spaced at 12 ft. Static load tests were conducted on individual posts, and dynamic tests of the fence were accomplished with rocks swung by a crane in the manner of a wrecking ball. Impact conditions in this dynamic test were not identical to those of rocks bounding down a slope, since attachment to the crane constrains rock trajectory. However, the test did demonstrate the resilience of strands in Flexposts and the capacity of steel gabion mesh in rockfall impacts. Analysis of data from this first test indicated that strain energy developed in the Flexpost strands was significantly less than rock kinetic energy and could not be the chief mechanism of energy dissipation. Instead, the fence arrests rockfall by developing tensions in its fabric of mesh and cables, and by altering rock trajectory. The rockfall capacity of the fence is not a function of the spring stiffness of Flexposts (Flexposts are not cantilevers resisting impacts), and therefore taller fences with similar post design could be expected to perform adequately.
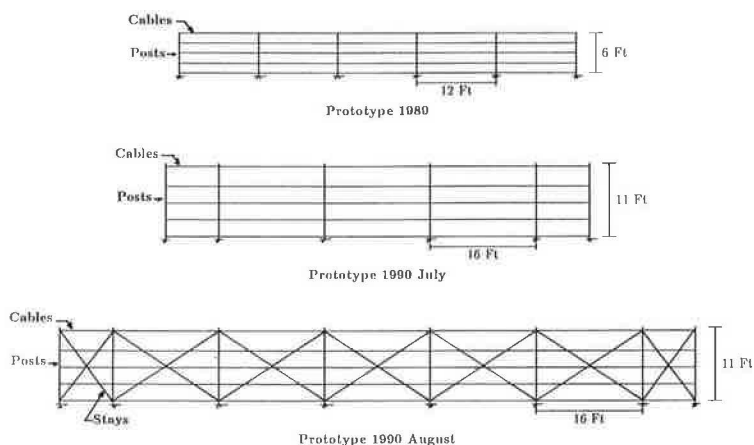

FIGURE 3   Flexpost rockfall fence prototypes: schematics for cables and posts.

In July 1990 a second prototype was built and tested. This fence was 11 ft tall with a post spacing of 16 ft. Another 11-ft fence was built and tested in August 1990. The August prototype included cable X-bracing in panels to protect post strands from tensile forces during rockfall impact. Both of the 1990 prototypes were tested with rocks rolling freely down a natural slope at a site near Rifle, Colorado. The slope is 500 ft long with an average slope of 66 percent. Rockfall velocities at impact as high as 50-ft/sec were observed in the Flexpost tests. Average rockfall velocity at impact was 32 ft/sec. Tests of other rockfall structures at this same site reported velocities as high 75 ft/sec (*1*). Rocks for prototype tests were numbered and weighed, three principal diameters were measured, and a pattern of paint dots was applied to make rock rotations more visible. The supply of test rocks ranged in weight from 145 to 9,700 lb. Rocks that hit Flexpost fence prototypes ranged from 265 to 6,040 lb. Rockfall impacts were recorded by two videocameras: one a sweep camera following the rock, and the other a fixed camera focused on the Flexpost fence.

The fence was marked with colored ribbons in the mesh to improve visibility on videotapes. The slope of the test site was also marked with ribbons at 10-ft intervals extending 60 ft uphill from the fence; these ribbons were used as reference points for estimating rock velocity from the videotapes. Time scales were added to the videotapes after testing. Data obtained from the videotapes included rock translational velocity, rock rotational velocity, vertical angle of rock trajectory, horizontal angle of rock trajectory, location of impact on fence, post rotations in response to impact, and damage to fence, if any. Rockfall weights, velocities, and energies are summarized in Table 1 and Figure 4.

During testing of the July prototype, 31 rocks were dropped resulting in 12 impacts with the fence (see Figure 5). Of these 12 impacts, 8 were stopped without damage to the fence, 1 tore the mesh fabric, and 3 overtopped the fence, which at the time was partially held down by previous rockfalls. Translational kinetic energies of rock impacts ranged from 4,700 to 166,000 ft-lbs. The July prototype was not damaged by impacts with translational kinetic energies as high as 42,600 ft-lb (a 1,490-lb rock travelling at 43 ft/sec), but was damaged by a rockfall at 44,100 ft-lb (a 1,550-lb rock travelling at 43 ft/sec). The July prototype appeared to have sufficient strength, but after repeated rockfall impacts, Flexpost strands had become permanently deformed. By the end of the testing, Flexposts would no longer rebound after rockfall impact, though the posts would remain vertical if righted. It appeared that the combination of large bending deformation and tension in the strands was the cause of damage.

TABLE 1 SUMMARY OF ROCKFALLS IN PROTOTYPE TESTS

| Test Date	Rock #	Rock Weight lbs	Rock Vel ft/s	Trans. K.E. ft-lbs	Rot. K.E. ft-lbs	Total K.E. ft-lbs	Observations
July 10, 1990	22	608	31.7	9,480	4,140	13,600	No Damage
	23	1,490	42.9	42,600	11,300	53,900	No Damage
	64	597	31.3	9,090	2,510	11,600	No Damage
	70	750	28.2	9,260	4,440	13,700	No Damage
	31	597	22.5	4,710	790	5,500	No Damage
	47	1,540	42.9	44,100	17,200	61,300	Tore Mesh
	46	1,390	37.5	30,300	6,880	37,200	No Damage
	4	3,600	-	-	-	-	No Damage
	41	1,510	41.1	39,600	18,600	58,200	Held Fence Down
	1	3,820	25.1	37,400	21,200	58,600	Overtopped, Fence Held Down
	65	949	42.9	27,100	6,140	33,200	Overtopped, Fence Held Down
	38	4,700	47.6	166,000	36,200	202,000	Overtopped, Fence Held Down
August 13, 1990	5	256	26.1	2,720	1,360	4,080	No Damage
	2	-	18.8	-	-	-	Tore Stay
	40	6,040	37.5	132,000	243,000	375,000	Tore Mesh
	64	597	33.3	10,300	1,830	12,100	Through Mesh Hole
	36	1,392	13.0	4,220	959	5,180	No Damage
	48	1,700	10.9	3,160	2,050	5,210	No Damage
	37	797	35.4	15,500	6,680	22,200	No Damage
	41	1,510	50.0	58,700	15,700	74,400	Tore Mesh
	34	592	35.4	11,500	4,100	15,600	No Damage
	9	1,620	15.1	5,660	2,550	8,210	No Damage
	12	1,360	37.5	29,600	6,730	36,300	Fabric Deformed
August 21, 1990	37	797	43.8	23,700	6,680	30,400	No Damage
	13	305	33.3	5,270	468	5,740	Bent Post
	14	1,280	33.3	22,200	11,300	33,500	No Damage
	64	597	17.3	2,770	3,290	6,060	No Damage
	70	750	28.6	9,560	2,310	11,900	No Damage
	4	3,600	21.4	25,700	18,300	44,000	Tore Mesh and Top Cable
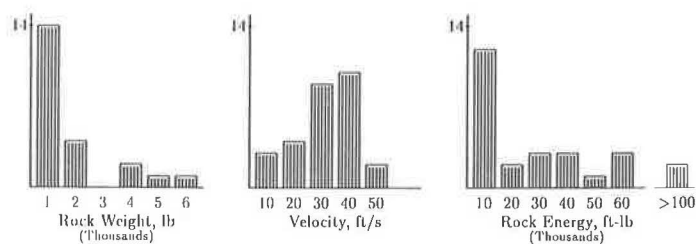
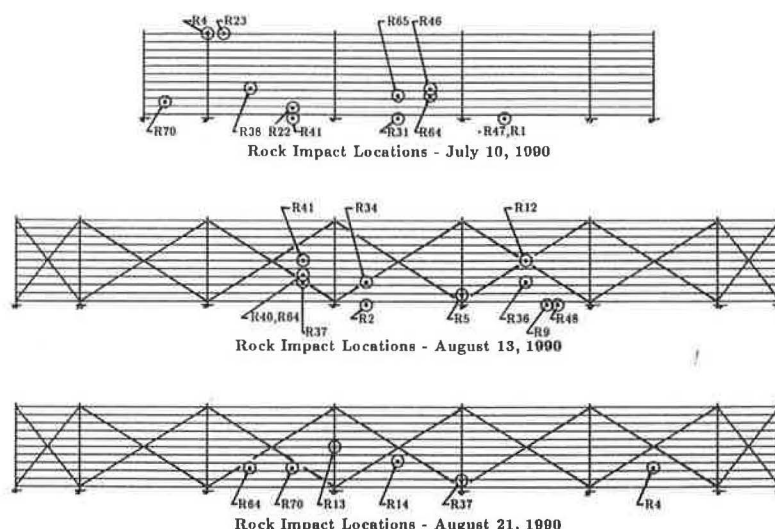FIGURE 4 Flexpost rockfall fence: summary of field test rockfalls.

FIGURE 5   Flexpost field tests: rock impact locations.

A third prototype with a revised design was tested on August 13, and again on August 21, 1990. This August prototype had the same post height and spacing as the July prototype and in addition, had diagonal cable stays forming X-bracing in fence panels connecting post tops to post foundations. These stays take tensions during rockfall impact and protect the Flexpost strands. The August prototype was tested by 17 rockfall impacts out of 39 attempts (Figure 5). Of the impacts, 12 were stopped without damage, 2 tore the mesh, 1 bent a Flexpost (the rock was stopped), 1 tore a diagonal stay, and 1 tore the mesh and the top horizontal cable. Translational kinetic energy of the rockfalls ranged from 2,700 to 132,000 ft-lb. The August prototype withstood an impact with a translational kinetic energy of 29,600 ft-lb without damage, and was damaged by an impact of 58,700 ft-lb. The Flexposts were able to rebound throughout the 2 days of testing with no apparent loss of elasticity in strand groups. The cable stays provided adequate protection for the strands.

ROCKFALL CAPACITY OF FLEXPOST FENCE

Field Tests

The 1990 rockfall tests confirmed the mechanism of rockfall response proposed after the 1989 test. For impacts of low kinetic energy, the Flexpost fence responds through inertial resistance and through straining in mesh, cables, stays, and posts. The fence structure itself absorbs the rockfall kinetic energy. For more severe impacts, inertial and stiffness resistances remain, but a second mechanism is also observed. Large, fast-moving rocks stretch the fence fabric taut, which imposes centripetal accelerations on rocks and can lead them to impacts with the ground. For severe impacts, it is the earth, not the fence, that absorbs rockfall kinetic energy. Direct tensions in mesh and cables provide the primary means of capturing falling rocks and of altering their trajectories. Spring stiffness of

Flexposts and inertial resistance of the fence masses are not significant contributors in halting large, fast-moving rocks.

The 1990 rockfall tests indicate that the rockfall capacity of the Flexpost fence is limited by the strength of the mesh. The mesh is usually the first element to fail, and its failure is associated with a specific level of rockfall energy. Other components were damaged in testing. In separate rockfalls, a diagonal stay was torn, a top cable was torn, and a Flexpost was bent. Posts and stays cannot deflect as easily as the mesh and may be damaged when hit squarely by a rock. Neither a bent post nor the loss of a stay will reduce the rockfall capacity of the fence, and indeed did not reduce the rockfall capacity of the prototypes. Loss of a stay may result in deformation of the strands in one post if there are repeated impacts after the stay is lost. The top cable failed along with the mesh in an impact directly on the top cable. Top cable failure is not a new more restrictive limit state for the fence.

Computational Analysis

A large-deformation, dynamic analysis program was developed to provide data on member forces, to compute fence response to rockfalls not observed in prototype tests, to establish the rockfall capacity of the fence, and to study design modifications. The program uses a time-step approach to compute node displacements and member forces during rockfall impact. The rock and the fence are treated as separate bodies. Information on rock position and on fence geometry is used to compute contact forces acting on fence nodes. Contact forces drive fence deformations and alter rock speed and trajectory. The analytical model of the Flexpost fence includes more than 300 lumped-mass nodes connected by a gridwork of mesh and cable members. Nodes occur at all post tops and foundations, in the mesh at post centerlines, and in the mesh at the midspan of mesh panels. Additional nodes 1 ft on center are placed in mesh panels near the location of rock impact.

This close spacing of nodes is required to model the contact of the rock with the fence fabric. Fence models with differing contact panels were prepared to handle various impact locations (see Figure 6). These models all correspond to the August prototype.

Mesh and cable members can carry tensions only (negative strains produce a computed zero-force value). Mechanical properties for cables have been taken from manufacturers' literature and developed from material tests for the gabion mesh (2). Flexposts are modeled as beam elements on spring mounts. Spring stiffness for post rotation is taken as the bilinear relation obtained from static tests. Rockfalls observed in the August tests were used as input rockfall cases for the dynamic analysis program (see Table 2). Fence deflections, member forces, and contact forces were computed. Analysis results were found to be in good qualitative agreement with observed performance of the prototype (for impacts that damage the fence, analysis results indicate member forces in excess of the expected breaking strength). Figure 7 shows a set of typical fence-deflected geometries during impact.

The influence of diagonal stays in the fence was investigated through a reanalysis of selected August rockfall cases using a fence model without stays. Analysis results indicate that mesh and top cable forces are lower for the fence without stays, because the fence is more flexible without them. Forces in intermediate cables are also lower, but the differences are not always great. Bottom cable force is increased. Lack of diagonal stays eliminates an important load path for transfer of fabric forces to the foundations and leaves much of this task to the bottom cable alone. Interior posts are always in compression when stays are present. Without stays, interior posts may experience net tensions.

To establish the rockfall capacity of the Flexpost fence, the dependence of member forces on rockfall energy, impact location (especially impact height), and design parameters such as post spacing was examined. It was found that member forces are proportional to the square root of rockfall kinetic energy. Plots of maximum forces in the top cable and in the

TABLE 2   FLEXPOST ROCKFALL FENCE: ROCKFALL INPUT CASES FOR DYNAMIC ANALYSIS

Test Date	Rock #	Rock Weight lbs	Impact Loc. X ft	Y ft	Z ft	Impact Vel. V_X ft/s	V_Y ft/s	V_Z ft/s
Aug.13	5	256	56	0	1	0.0	25.7	4.5
	40	6,040	36	0	4	-6.5	30.7	21.5
	64	597	36	0	4	-5.8	31.3	11.4
	36	1,390	64	0	3	6.5	11.3	0.0
	48	1,700	68	0	0	0.0	10.9	0.0
	37	797	36	0	3	3.1	34.9	6.1
	41	1,510	36	0	5	0.0	47.0	-17.1
	34	592	44	0	3	0.0	34.2	9.2
	9	1,620	67	0	1	-5.2	14.2	0.0
	12	1,360	64	0	5	0.0	37.5	0.0
Aug.21	37	797	56	0	1	0.0	43.1	7.6
	13	305	40	0	5	0.0	31.3	-11.4
	14	1,280	48	0	4	0.0	30.2	14.1
	64	597	29	0	3	0.0	15.7	7.3
	70	750	35	0	3	0.0	24.8	14.3
	4	3,600	80	0	3	-7.3	18.0	9.0

Coordinate origin is ground surface at the end of the fence.
X is measured along the fence. Z is the gravity axis.

interior stay cables are shown in Figure 8. Despite some scatter, a linear dependence is apparent for all components (correlation coefficients exceed 0.9). Maximum member forces only have a weak dependence on impact location. This result can be understood from an examination of deflected shapes of the fence. Most rockfalls are ultimately stopped near the top of the mesh, even when the initial impact occurs near the bottom. Rock impact near the bottom of the mesh will deflect the fence, and the fence will in turn exert forces tending to lift the rock. As a result, the pocket in the mesh that arrests the rock usually forms somewhere from the midheight to the top of the mesh. The Flexpost fence ushers rockfalls to its more compliant region, so the influence of initial impact height is minimized. It is therefore possible to state the rockfall capacity of the Flexpost fence in terms of limiting rock mass and velocity, without additional limits related to impact location within the fence. The curve of limiting rock velocity versus weight is presented in Figure 9 and indicates a limiting velocity of 41 ft/sec for a 1,000-lb rock and a limiting velocity
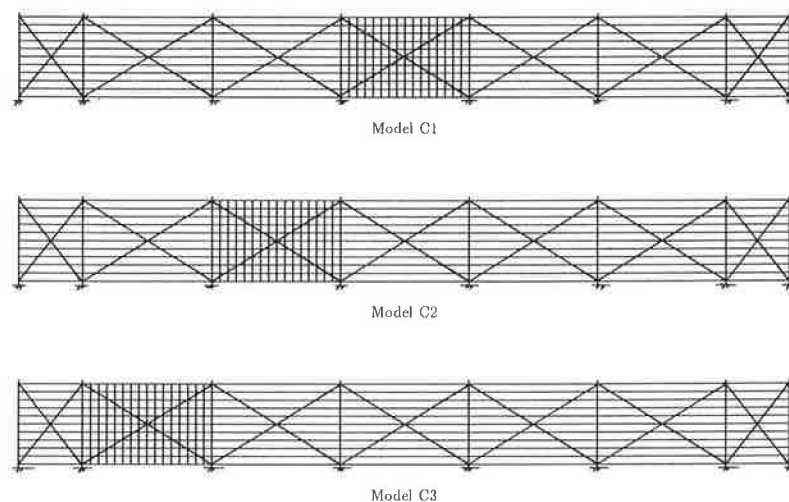

Model C1

Model C2

Model C3

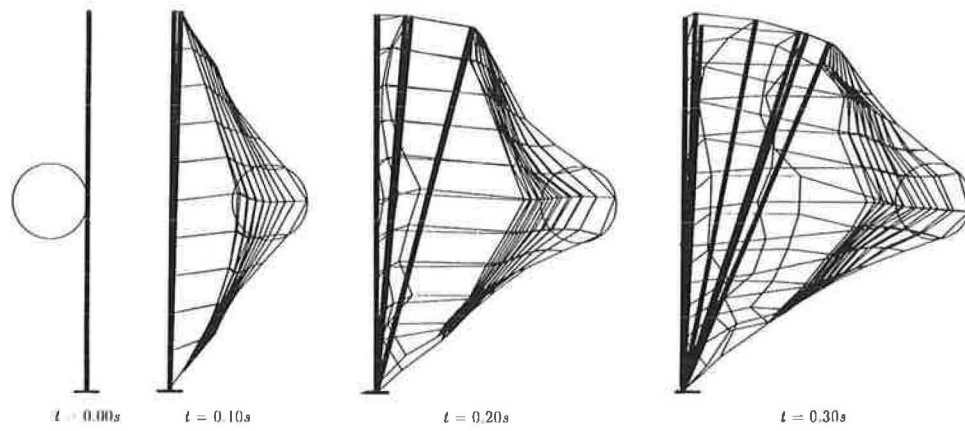FIGURE 6   Flexpost rockfall fence: models for contact problem.

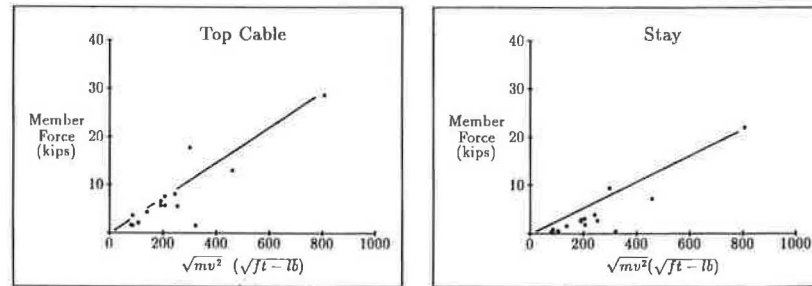FIGURE 7   Flexpost rockfall fence: response to rock impact.

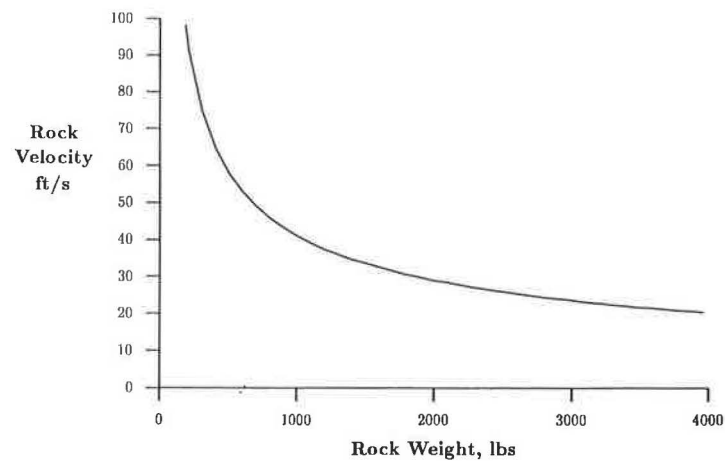FIGURE 8   Flexpost rockfall fence: member force versus square root of rockfall kinetic energy.

FIGURE 9   Flexpost rockfall fence: limiting rock velocity versus rock weight.

TABLE 3 FORCES
IN COMPONENTS
LIMIT STATE:
MESH RUPTURE

Component	Force lbs
Top Cable	5,500
Rnf. Cable, Top	3,800
Rnf. Cable, Mid	6,900
Rnf. Cable, Bott	5,500
Bottom Cable	10,600
Stay, End	9,200
Stay, Interior	5,800

of 29 ft/sec for a 2,000-lb rock. Forces in other members corresponding to this limit state are given in Table 3.

For foundations at end posts, shear force at mesh limit can be expected to be about 5,000 lb and uplift about 5,700 lb. Interior post foundation will experience shear force of 3,300 lb and uplift of 800 lb. Additional information on Flexpost fence analysis may be found elsewhere (3).

FLEXPOST FENCE USE IN COLORADO

The first service installation of a Flexpost fence was completed in 1990 along I-70 in Glenwood Canyon. This fence has a total length of 580 ft and is similar in design to the 1989 prototype. The bid price of the installation was $65/ft. Rockfall hazard at the site is estimated to be as severe as a 700-lb rock travelling at 45 ft/sec. Rockfall hazard was estimated from data obtained in a site survey and statistical information on rock velocities and bounding heights computed by the Colorado Rockfall Simulation Program (1,4). Additional installations are planned for several miles of fence along highways in Colorado, beginning with a major rockfall remediation project in Glenwood Canyon.

In addition to its effectiveness as a protective structure, and its obvious economy, the Flexpost fence is easily maintained. There are no structural members out of the plane of the fence to hamper movement of equipment. Mesh can be easily repaired by patching, and other components may be either spliced or replaced piecewise as necessary. Compared with other rock-fall protective structures, the visual impact of the Flexpost fence is minimal.

SUMMARY

Flexposts are the important source of elastic compliance in the rockfall fence. Compliance allows the fence to exercise its fabric of mesh and cables in tension as the primary load-carrying members. Since rockfall capture is achieved by direct tension in the fabric, the rockfall capacity of the fence does not depend on the spring stiffness of Flexposts. Impact height, a concern for structures that function by developing resisting base moment, is not a concern for the Flexpost fence. On the contrary, since centripetal force varies inversely with the radius of a rock's arc, high impacts mean reduced forces in the fabric. Flexpost fence height is limited only by dead weight demand on posts. Flexposts must possess sufficient stiffness to keep the fence upright. For a post spacing of 16 ft, the limiting fence height is about 15 ft for the present Flexpost construction.

The Flexpost rockfall fence minimizes impact forces by allowing large deflections. Fence deflections are elastic; the fence rebounds after impact. Two years of testing, development, and analysis have produced an efficient structure of known capacity and proven performance.

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