Walking speed, ship listing and regulations

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Abstract

Ship listing and dynamic ship motion have a dramatic effect on the propagation speed of passengers. This was shown in a series of experiments in the TNO Ship Motion Simulator and some level and listed mock-ups. Comparison with the walking speeds and densities as issued in the Fire Protection Concept for buildings by the Netherlands Ministry of Inner Affairs shows that those data are based on young people only, that velocities on stairs are much too optimistic (only descending) and that the proposed densities will be never encountered during ship listing or ship motion. The interim IMO guidelines are more conservative, but there too no slowing down of the walking speed during ship listing or ship motion is incorporated. It is just in view of the passenger population of cruise liners that on the basis of the present data adjustment of the IMO guidelines is justified.

Introduction and history

Ship disasters like the capsizing of the HERALD OF FREE ENTERPRISE in 1987 and the sinking of the ESTONIA in 1994 showed that safety was insufficient. That is why, since these disasters, actions to improve safety on board ships have gathered momentum. This also explains much of the thinking behind the BriteEuram project "Mustering and Evacuation of Passengers: Scientific Basis for Design" or MEPdesign for short. Within MEPdesign (study I) we collected data on how passenger (walking) speed is influenced by the unstable ship environment (Bles et al., 2000). In a follow-up study (study II) we completed the data set (Bles et al., 2001). Now data are available for static ship listing and dynamic ship motion conditions for subjects of all age categories concerning walking speed in open spaces and in corridors, while ascending or descending stairs. We also examined delays caused by opening doors. Together, the data cover the whole path of passengers moving to their muster station, and enable reliable simulation of propagation speed during mustering. In the present paper these data are compared to regulations for evacuation of buildings and ships.

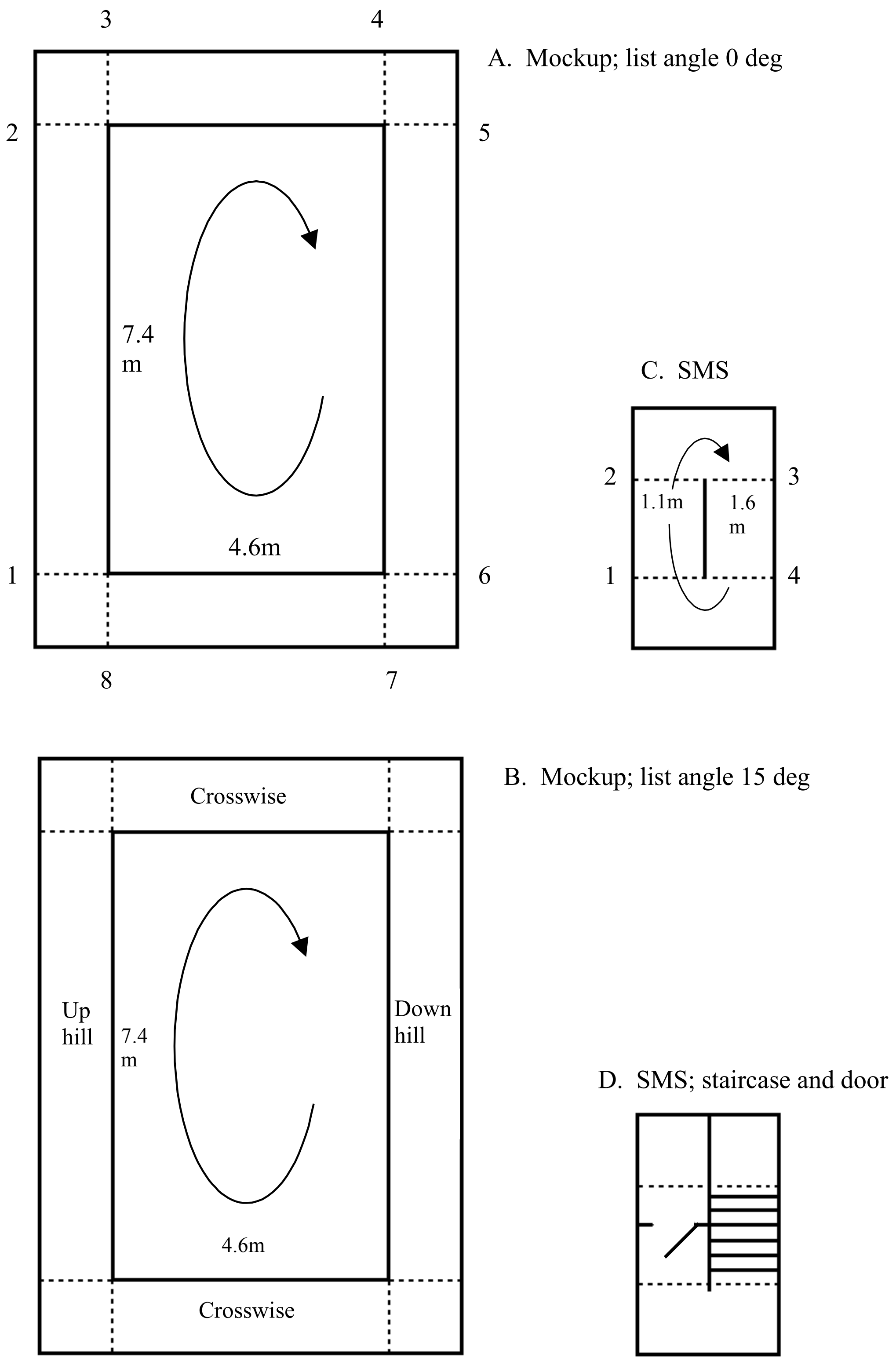

Fig. 1 Horizontal mock-up (A), over 15 ° tilted mock-up (B), and SMS lay-outs (C and D) as used in the MEPDesign study (I) and the follow-up study (II). The width of all corridors was 1.1 m. The numbers 1-4 and 1-8 represent locations of LED sensors, sensing passing at the dotted lines, which were always at 1.1 m distance from the end of a corridor.

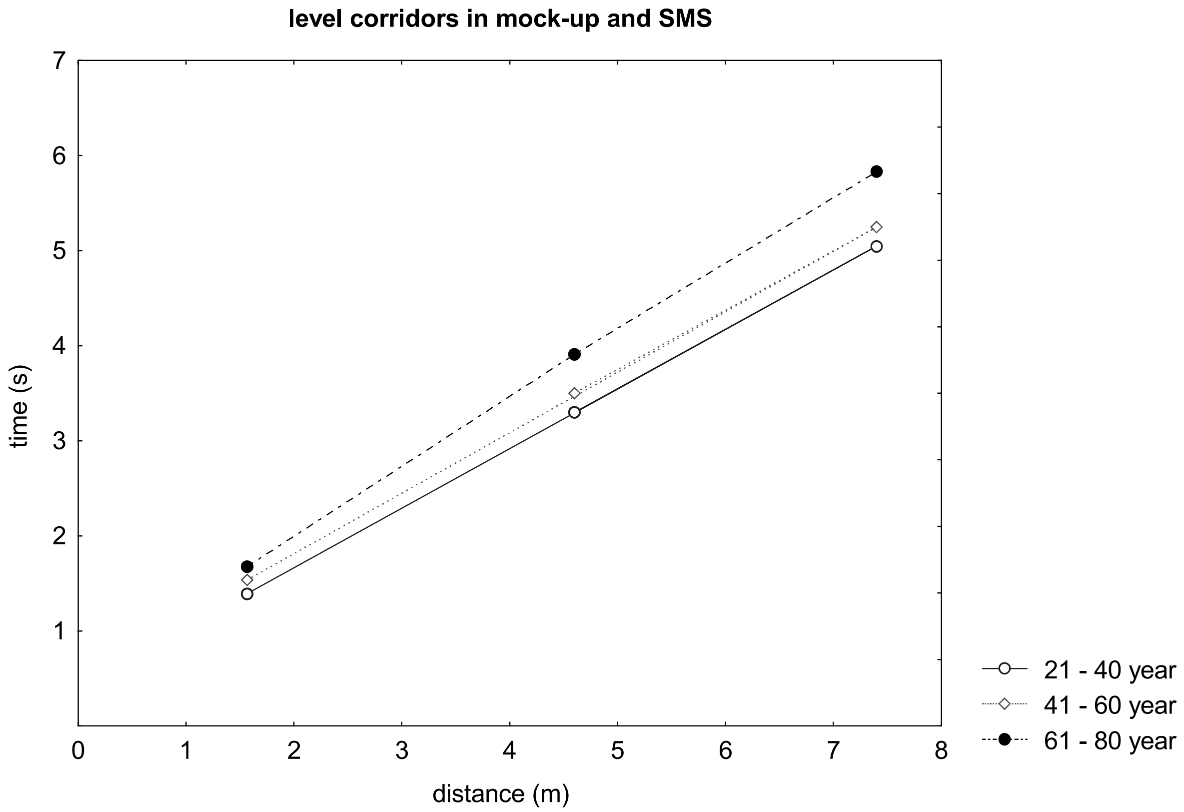
level corridors in mock-up and SMS
time (s)
distance (m)
0
1
2
3
4
5
6
7
8
21 - 40 year
41 - 60 year
61 - 80 year

Fig. 2 Relationship between walking time and distance for the corridors of 1.6 m in the SMS (configuration C), and the corridors of 4.6 m and 7.4 m in mock-up A.

Experimental data

Experiments were performed in two mock-ups and in the TNO Ship Motion Simulator. The floor plan of these devices is shown in Fig. 1. One of the mock-ups was horizontal (mock-up A), the other mock-up was completely identical, but listed as a whole over 15° (mock-up B). The cabin of the SMS was much smaller, but allowed for studying walking in corridors tilted laterally up to 15° or walking in corridors tilted upward or downward up to 20° (configuration C or D, Fig. 1). Both the mock-ups and the SMS were completely closed: Subjects inside had no view on the outside world. Subjects of different age categories participated, from 20 – 80 years old. Walking velocities were measured by using an LED sensor system measuring the time subjects passed that sensor (dotted lines in Fig. 1). Knowing the distance between two successive sensors, walking velocity could be calculated be over that trajectory. At the stair (SMS configuration D, Fig. 1), each of five successive steps was accommodated with sensors. For details of the experimental procedures reference is made to Bles et al (2000, 2001).

Data on walking speed have been reported extensively elsewhere (Bles et al. 2000, 2001). They can be summarised as follows for static ship listing.
Walking in corridors: With increasing ship listing from 0° up to 20° walking speed reduced steadily up to about 35% if people went uphill, 15% if people went downhill, and 20% if people walked in laterally tilted corridors. Seniors were about 15% slower than the young or middle-aged. These findings were similar for experiments in the Ship Motion Simulator (SMS) and in the Mock-ups. The maximum walking velocities were, however, not the same: In the SMS the velocities were slower than in the Mock-ups. In the MEP-design experiment subjects walked in both the mock-ups and the SMS. In Fig. 2 their velocities on level floors for the different age categories and the different corridors (cf. Fig. 1) are shown. Apparently a linear fit is quite well possible. This suggests that subjects did not reach their steady velocity before they passed the first sensor, and perhaps did not maintain their velocity before they passed the last sensor. However, because the linear fit is quite good, the behaviour of the subjects is the same in each corridor. This as such is not surprising, since the space in the corners was identical for each corridor: 1.1 m x 1.1 m. The slope of the fit shows that the constant walking speed was the same for the young and middle-aged groups (5.7 km/h on the average, i.e. 1.58 m/s), and 12,5 % slower for the seniors (5.0 km/h on the average, i.e. 1.4 m/s). Data of Study II after application of this conversion are shown in Table I.

Stairs: Ascending stairs was ~ 30% slower with the stair tilted upward 20° (for seniors ~ 35%). Ascending a downward tilted stair did not hinder people. Descending stairs was ~ 15% slower when the stair was tilted 20° upward. Descending a downward tilted stair over 20° made people ~ 20% slower (seniors ~ 25%). A laterally tilted stair hardly influenced the climbing speed (maximally 5% at a list angle of 15°.
For certain reasons we defined in our studies the climb velocity as projected on the floor under the stair. In other studies the climb velocity is indicated along the climb line. If we convert our data to the velocities along the climb line, we get the results as shown in Table I for young people and for seniors.

Doors: Passing a door caused delays of 1.5 or 0.5 s depending on whether the door swung inward or outward, respectively. List angles of 20° caused an additional delay of 2 s for seniors, especially when the door was about 30 kg and had to be opened upward.

Table I. Results of walking speed in corridors and on stairs for young people (20-40) and seniors (60-80) from study II (Bles et al., 2001). The results have been made compatible with the values as presented in the Tables II - V.

Type of Facility	Density (p/m^2)	Walking velocity (m/s)	Specific Flow (p/ms)
Corridor			
- level	< 0.5	1.6 (seniors: 1.4)	-
- 20° upward tilt	< 0.5	1.1 (seniors: 0.9)	-
- 20° downward tilt	< 0.5	1.5 (seniors: 1.3)	-
- 15° tilted laterally	< 0.5	1.4 (seniors: 1.2)	-
Stair (up)			
- level	< 0.5	.62 (seniors: .57)	-
- 20° upward tilt	< 0.5	.44 (seniors: .35)	-
- 20° downward tilt	< 0.5	.60 (seniors: .56)	-
- 15° tilted laterally	< 0.5	.56 (seniors: .53)	-
Stair (down)			
- level	< 0.5	.70 (seniors: .62)	-
- 20° upward tilt	< 0.5	.56 (seniors: .48)	-
- 20° downward tilt	< 0.5	.55 (seniors: .43)	-
- 15° tilted laterally	< 0.5	.55 (seniors: .52)	-

With and without handrails: An important finding was that people needed the handrail during ship listing. Otherwise they drifted towards the lower wall of the corridor. This imposes a considerable reduction on the density, the number of subjects per m^2, and consequently on the specific flow through the escape ways, that is, the number of passengers exiting per m per s.

Dynamic movements: Stimuli for dynamic ship motion were sinusoids with different frequencies and various amplitudes. We found that walking speed slowed down with increasing frequency and with increasing amplitude, being about 15% slower at a stimulus frequency of 0.89 radians/s with an amplitude of 10°. The floor of the cabin was 2 m above the axis of rotation, so our pitch and roll motion always introduced a (small) parasitic linear acceleration component. At larger distances from the axis of rotation, the additional linear accelerations will increase and will be the primary forces slowing people down: the capacity of corridors and open spaces decreases, because passengers need to hold a handrail if these linear accelerations exceed 0.5 m/s^2.

Regulation concepts for building evacuations

Research on building evacuations in case of fire has led to a general fire protection concept in the Netherlands (Dutch Ministry of Interior Affairs (BiZa), 1995). In order to calculate evacuation times given a particular building, formulae for walking speed and specific flow have been summarised for corridors, stairs and doors by Stichting Bouwresearch (SBR, 1984). The subsequent sections discuss these formulae and their consequences for listed surroundings. Especially concepts like crowd density (number of persons per m², denoted as p/m²) and the capacity or specific flow (number of persons per m per s, denoted as p/ms), which have not been examined in our studies, deserve attention, since these parameters are of paramount importance for calculation of evacuation times. In our studies we looked primarily at individual behaviour, which means that density was <0.5 p/m².

Table II Approximations for walking speed and specific flow in corridors as a function of subject density for calculating building evacuation times (BiZa, 1995).

Type of Facility	Density (p/m²)	Walking speed (m/s)	Specific flow (p/ms)
Corridors	<0.5	1.60	-
	1.0	1.31	1.31
	1.5	0.92	1.38
	2.0	0.73	1.46
	2.5	0.61	1.52
	3.0	0.53	1.59
	3.5	0.47	1.65
	4.0	0.43	1.72
	4.5	0.40	1.80
	5.0	0.37	1.87
	5.5	0	0

Corridors and open spaces: The SBR-report quantifies the effect of density on walking speed. Walking speed starts to slow down at a density of 1 p/m², and is virtually zero at a density of 5.5 p/m². In the publication of the Ministry (BiZa,1995) approximations for walking speed and specific flow have been summarised as a function of density, as shown in Table I. These numbers can be used to calculate the capacity of corridors and open spaces to estimate the evacuation time. It should be noted that the specific flow increases with increasing density up to a density of 5 subjects/m².

These BiZa approximations are not directly applicable to ship evacuation calculation. First, it should be noted that even healthy seniors are slower than younger subjects (Table I). For ships it might be wise to use these low velocities in the calculation. Second, the walking speed slows down linearly with increasing list angle. Third, subjects walk in laterally listed corridors using the handrail. Without a handrail about half of the people deviates towards the underlying wall (as observed at a 15° list angle). We may assume that at an angle of 20° everybody will cling to the handrail. Handrails are less important for walking up or down, but most people will prefer using a handrail at angles of 20° or beyond. This implies that for a listed ship specific flow should be calculated with density defined as *number of subjects per m handrail* rather than *number of subjects per m²*. Maximum density under these circumstances is most likely smaller than 2, which means a considerable reduction of specific flow, especially in wide corridors and open spaces.

A fourth point is that listing makes part of the floor inaccessible because subjects and wall make a certain angle. In narrow corridors that therefore barely permits two people to walk side by side, so listing reduces the capacity to one person at the time.
Similar considerations hold for ship motion if the horizontal linear accelerations due to ship roll exceed $0.5 m/s^2$ since then subjects cannot maintain their postural control without a handrail (Bles et al., 2001). These linear accelerations become the most important threat for postural control during ship motion when subjects are at eccentric positions, far above the main roll axis of the ship.

Table III Approximations for descending speed and specific flow on stairs as function of subject density for calculating building evacuation times (BiZa, 1995).

Type of Facility	Density (p/m^2)	Descending speed (m/s)	Specific flow (p/ms)
Stairs	<0.5	0.80	-
	1.0	0.80	1.31
	1.5	0.80	1.38
	2.0	0.64	1.46
	2.5	0.51	1.52
	3.0	0.43	1.59
	3.5	0.37	1.65
	4.0	0.32	1.72
	4.5	-	
	5	-	
	5.5	0	0

Stairs: In the BiZa concept (1995) data on stairs have been summarised, which are shown in Table III. For evacuation of buildings, these approximations can be used to calculate the specific flow on stairs and estimation of the evacuation times. However, ship listing and ship motion require different approaches in the calculation. Some points need to be mentioned here. First, for most building evacuations, descending stairs is more common than ascending. For evacuation of ships, however, ascending stairs is also relevant, and, because ascending goes slower than descending, more data is needed, like the data presented in Table I. Again, just as with corridors, climbing speeds go down with increasing list angle, and seniors, even if healthy, are slower than younger subjects. Important is that climbing tilted stairs requires handrails, independent of the direction of the tilt. This implies that calculating specific flow on tilted stairs should work with density defined as *number of subjects per m handrail* rather than *number of subjects per* m^2. It is obvious that this leads to densities which are considerably lower than in buildings.
Lateral tilt makes part of the floor inaccessible. In consequence, effective stair width is reduced. This adds to the problems of people's penchant to cling to a handrail. Similar considerations are valid for ship motion: people need a handrail.

Doors: For evacuating buildings, the approximations of the SBR-report (1984) seem valid: 2.4 p/ms for a door width of 1.0 m, to 4.8 p/ms for a door width of 2.0 m. For ship evacuation, listing and ship motion require different calculation strategies. For instance, opening doors might be problematic, seniors need more time than younger people, and they may injure themselves if the door is heavy and swings towards them by the force of gravity. Arguments about density and specific flow are pretty similar to those mentioned in the sections on corridors and stairs.

Regulation concepts for ship evacuation

The International Maritime Organisation has issued recommendations on evacuation analysis which are partly shown in Table IV (MSC/Circ.909, 1999). We see in Table IV a further simplification of the relationships presented in the SBR-report on walking speed, density and specific flow for corridors and stairs, as shown in Tables II and III. The IMO proposal divides the conditions in a low, an optimum, a moderate and a crush condition, for corridors and for stairs. This refers to the specific flow in these conditions, which is highest for the 'optimum' condition. They split up the conditions for stairs in ascending and descending, which makes sense for the evacuation from ships. Comparison of the walking speed and the specific flow for the specified densities with those of the BiZa concept (Tables II and III), shows that the IMO data are more conservative (they remain on the safe side). For instance, unperturbed walking speed is 1.4 m/s, whereas in the SBR report it is 1.6 m/s. Compared with the data from our own study, 1.4 m/s is exactly the walking speed of our senior subjects, and 1.6 m/s the walking speed of our younger age group, as shown in Table I. For use of an evacuation analysis it makes sense to use the walking speed for seniors. However, one should realise that the original walking velocities from our studies I and II are lower, because our trajectories involved corners during concourse walking, and rounding corners slows down considerably (Bles et al., 2000). The estimate for specific flow in Table IV is also considerably less for increasing densities compared to Tables II and III. This seems to be more realistic, certainly in case of ship listing. We have no information from our current experiments on walking speed as a function of density, unless what is mentioned on the uselessness of density defined as p/m² in case of ship listing.
For stairs the climbing speed of 0.8 m/s for a level stair as indicated in Table III has been split up in 0.8 m/s for ascending stairs and 1.0 m/s for descending stairs. Our data suggest that people are much slower on stairs as shown in Table I, so in this case the values as proposed by the IMO are rather high. For the different densities on stairs, we have the same comments as for corridors: during ship listing everybody needs a handrail, so it is the number of handrails available on a stair which determines the density, and as such the specific flow.

Table IV. Approximations for speed of persons and specific flow as a function of density for different facilities for the calculation of evacuation times on ships as presented by the IMO (1999).

Type of facility	Condition	Density (p/m²)	Speed of Persons (m/s)	Specific Flow (p/ms)
Corridors	Low	< 1.9	1.40	0.76

	Optimum	1.9 to 2.7	0.70	1.30
	Moderate	2.7 to 3.2	0.39	1.10
	Crush	> 3.2	0.18	0.55
Stairs (down)	Low	< 1.9	1.0	0.54
	Optimum	1.9 to 2.7	0.50	0.94
	Moderate	2.7 to 3.2	0.28	0.77
	Crush	> 3.2	0.13	0.42
Stairs (up)	Low	< 1.9	0.80	0.43
	Optimum	1.9 to 2.7	0.40	0.75
	Moderate	2.7 to 3.2	0.22	0.62
	Crush	> 3.2	0.10	0.32

Recently there were comments on these interim guidelines like the one from the Working Group, Sub-Committee on Fire Protection (FP 45/WP.6, 2001). They suggest a further simplification in suggesting only one typical speed of persons and specific flow, defined for corridors and stair (up and down), as shown in Table V.

Table V. Approximations for speed of persons and specific flow for different facilities for the calculation of evacuation times on ships as presented by the IMO working group (2001)

Type of Facility	Speed of Persons (m/s)	Specific Flow (p/ms)
Corridors, doorways	0.67	1.3
Stairs (down)	0.55	1.1
Stairs (up)	0.44	0.88

Since they claim to have used the same source for these data as the IMO guidelines, these values suggest a density of about 2 subjects per m². For listing this makes sense, because then the densities higher than 2 p/m² are unlikely to occur as discussed previously. It implies that direct comparison with our data is difficult, because our data refer to unobstructed walking.
Similar considerations hold for the walking speeds on stairs: our data refer to unobstructed walking. If we compare the given specific flow with the table as presented in the IMO Guidelines, here too a density of about 2 p/m² is considered. This implies for them a decrease of the climbing speed with about 50 %, which means that in our view these climbing speeds are too high: 50 % of our senior climbing speeds would be ~0.28 m/s for descending and ~0.31 m/s for ascending.

In both the IMO Guidelines and the Comments, no attention has been paid to the strong decrease in walking speed and capacity of open spaces due to ship listing.

Conclusions and recommendations

Data have been gathered on the effects of ship listing and ship motion on the walking speed in corridors and on ascending and descending stairs. The time delays caused by opening doors have been examined as well. The test subjects varied in age from 18 – 82 years old. The experiments were performed in the TNO Ship Motion Simulator. The experiments were accomplished to complete the data set gathered in the European MEPdesign project.
The main findings are that walking speed decreases significantly with increasing ship listing (for instance, up to 30 % for walking uphill in a tilted environment of 20°). For seniors (age category of 61-83) a similar decrease has been found. Seniors were in all conditions about 10 – 15 % slower than younger aged subjects. For ascending and descending stairs similar observations have been made, be it that the reduction in ascending or descending is even more impressive than for walking in corridors.
A second observation in our experiments was that under listing conditions people need handrails, especially on a stair. This fact may decrease the capacity or the specific flow dramatically. The data as obtained were in accordance with the data from the MEPdesign project as far as available. The ship motion data also show a reduction in walking speed, but of more interest is that the density will decrease as soon as the linear accelerations due to an eccentric position during roll motion exceed a value of 0.5 m/s^2, because passengers will have problems in keeping upright posture without handrails.

The interim IMO guidelines are too optimistic on the walking speed on stairs, especially for senior people. Moreover, they ignore the fact that ship listing may affect the capacity or specific flow dramatically, not only because of the decrease in walking or climbing speed under ship listing conditions, but also because the density will be considerably less under listing conditions: It is not the width of a corridor (or door) which determines the specific flow under ship listing conditions, but the number of handrails available. Capacities of corridors and stairs may decrease by a factor 4 to 10 if we calculate the evacuation time on the basis of our data compared to the IMO guidelines or BiZa concept.

It is therefore recommended that the IMO Guidelines will be reconsidered in view of our data, especially for RO-RO passenger vessels, since the present guidelines may give far too optimistic estimates of the total evacuation time in case of ship listing.
The differences in climbing speed and associated difficulties for climbing upward, or climbing laterally tilted corridors, suggest that it is worthwhile to consider the exact orientation of stairs on board of ships in more detail.
It is also recommended to investigate the effect of density on the walking speed under listing conditions in more detail. Data will be useful for evacuating buildings as well as other vehicles like trains and planes.

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